ANISOTROPIC BEHAVIOUR OF UNIDIRECTIONAL FIBROUS COMPOSITES UNDER TENSILE AND IMPACT LOADS

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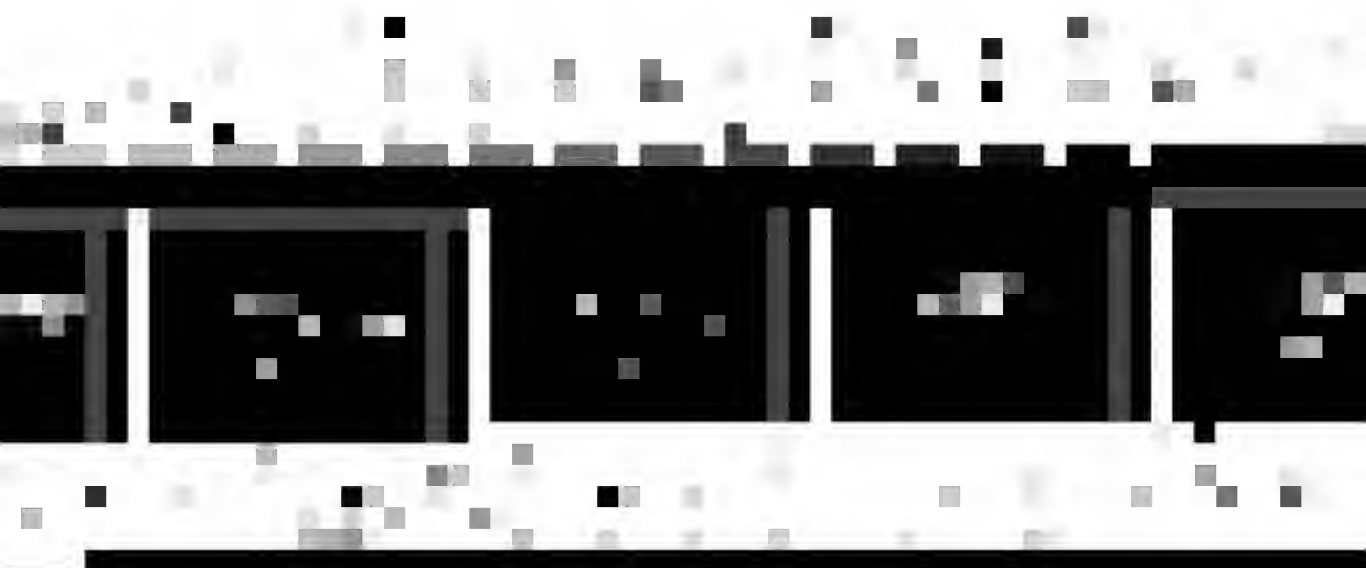
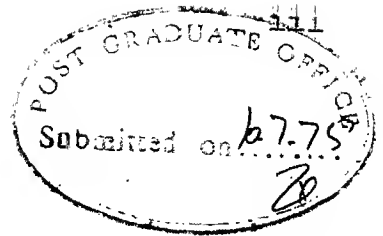INDIAN INSTITUTE OF TECHNOLOGY KANPUR

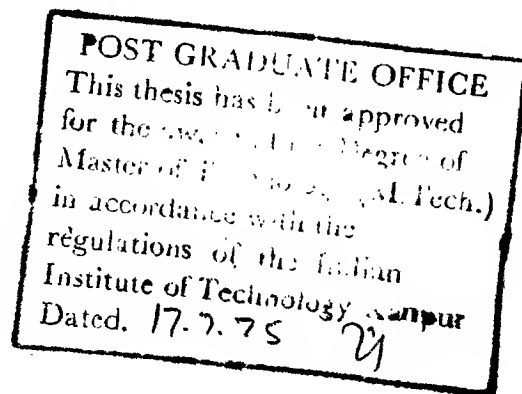JULY 1975

To

SUSHMA, SURABHI & SAMIR

CERTIFICATE

This is to certify that the thesis entitled
"Anisotropic Behaviour of Unidirectional Fibrous
Composites under Tensile and Impact Loads" by
Jetha Nand Narang is a record of the work carried out
under my supervision and has not been submitted else-
where for a degree.

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SYNOPSIS

Continuous fiber-reinforced composite materials are an important class of modern materials. Their high strength to weight and modulus to weight ratios, controlled anisotropy and formability make them superior to many conventional materials for various applications. The strength, elastic modulus and many other properties of such materials are highly direction dependent. The present studies were carried out to establish quantitatively the angular dependence of their properties experimentally. A number of specimens of glass fiber reinforced epoxy with different fiber orientations were subjected to tensile and impact loads. The tensile tests provided the data to study the stress-strain behaviour, the angular dependence of elastic modulus and strength of the composite materials. Charpy impact tests were employed to study the behaviour of these materials under impact loads. The impact loads were applied parallel and perpendicular to the plane of the composite materials. All the specimens subjected to static tensile or impact loads were carefully examined to investigate the mechanism of failure of the composite materials. The results were compared with the experimental and theoretical results of other investigators wherever available.

CHAPTER I

Demands of materials imposed by today's advanced technologies have become diverse and severe that they often cannot be met by simple single component materials acting alone. It is frequently necessary to combine several materials into a composite to which each constituent not only contributes its share, but whose combined action transcends the sum of individual properties and provides new performance unattainable by the constituents acting alone.

Many of the new materials being developed are multiphase or in the composite family. For example, glass fibers are used extensively to reinforce organic matrices. Dispersion strengthened alloys consist of a finely divided second phase distributed in a crystalline matrix. Glass-ceramics make use of controlled crystallization from a glassy melt. Rubber reinforcements are used in glassy polymers to enhance the impact strength of the brittle matrix. In all the cases, the properties of the composite material depend on the properties of the individual components, their distribution, and their physical and chemical interaction.

The many outstanding features of high performance fibrous composites have made them attractive
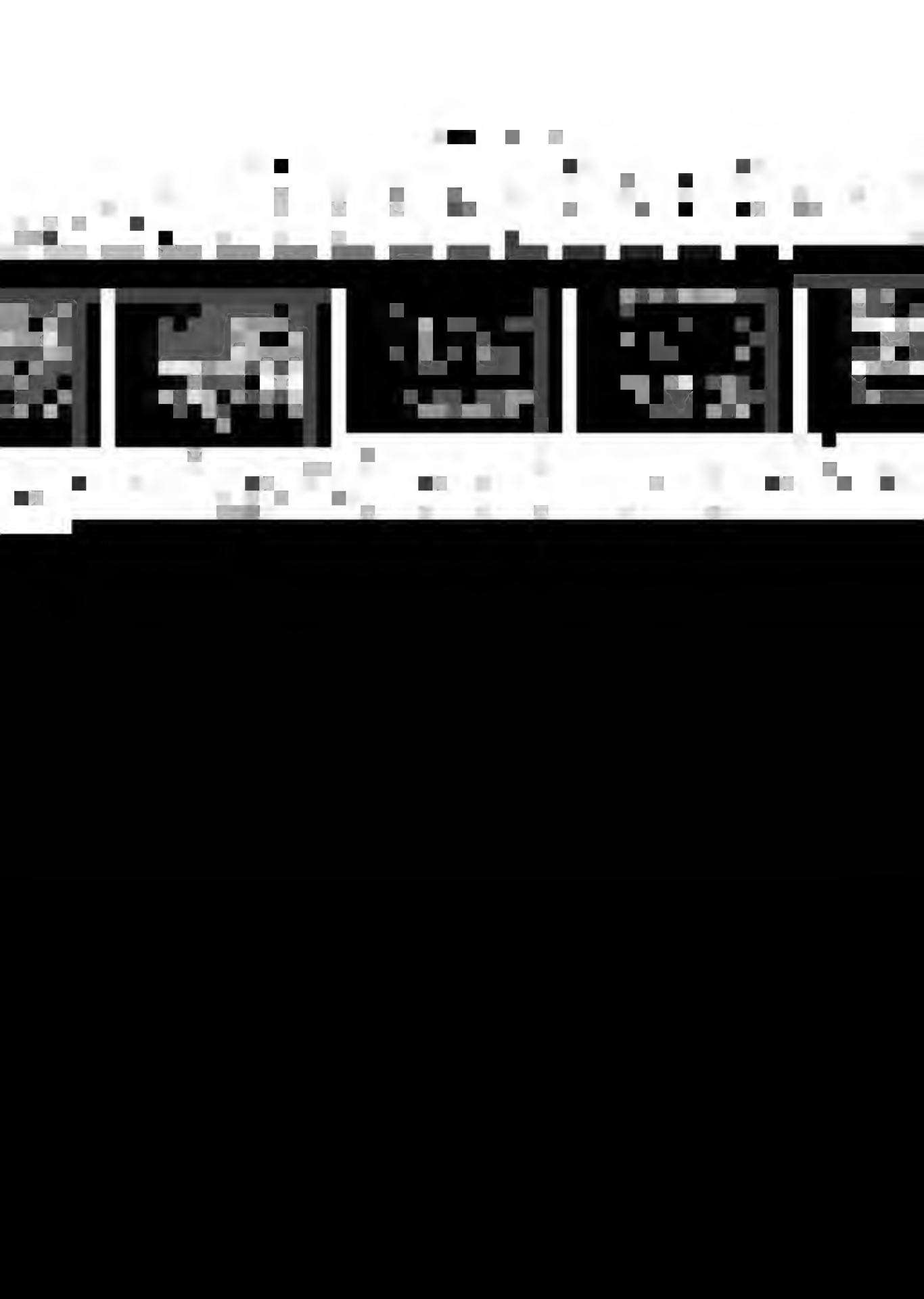
structural materials. Oriented fiber reinforcement offers a strengthened and stiffened material having a high strength-to-weight ratio. Additional advantages of fibrous composites include improved behaviour at high temperature, the production of structural forms otherwise inconvenient or impossible and controlled anisotropy in physical properties.

In a unidirectional fiber-reinforced composite, the matrix serves two purposes, namely, to transfer the load to the fibers and to bind the fibres together. In the case of continuous fiber reinforcement the stress may be assumed to be constant over the whole length of the fibers[1] . The principal purpose of the matrix is to bind the fibers together. The strength of the composite is then dependent upon the strength of the fibers. However, in studying the fracture of continuous fiber composites, it has been found that individual fibers fail well before the entire composite fractures. In this case the load transferred to the broken fibers by the matrix and the interfacial conditions may thus influence composite fracture [2,3] .

In considering the performance characteristics of the fiber reinforced systems, many factors influence overall system response. Among these are constituent physical and mechanical properties, interfacial bonding and such geometrical properties as size.

shape and orientation of reinforcements. Associated with above factors is the influence of crack initiation and propagation through reinforced systems and its relationship to overall system response [4].

Mullin et al [5] studied the critical fracture mode of an epoxy matrix in the vicinity of a break in a high modulus high strength filament. They have predicted that the failure modes may involve crack propagation in the matrix or the debonding of the filaments from the matrix. Glass fiber reinforced epoxies are expected to exhibit the latter mode of failure. Studies by Goggin [6] on carbon fiber composites have demonstrated that elastic constants of the composites parallel to the fiber axis can be predicted from the knowledge of the elastic constants of the fibers and the matrix. Sih and Chen [7] have shown that at low fiber - orientations unidirectional composite specimens fail through a combination of fiber breaking, matrix cracking and fiber-matrix debonding. The uniaxial fibrous composites when loaded parallel to the fibers, depending on the elastic properties of the constituents, may either fracture across the fiber or split along the fibers.

The effects of fiber-orientation on the physical properties of composites have been studied by Knibbs and Morris [8]. They have established the angular

dependence of the composite properties such as Young's modulus, electrical resistivity and thermal expansion coefficient of carbon fiber/epoxy system.

In very broad terms the longitudinal properties of uniaxial composites are controlled by the fibers where as the transverse properties are controlled by the matrix. Consequently in a system such as glass fiber/epoxy resin, high degrees of anisotropy are manifested. It is generally agreed that because of the marked anisotropy the properties of uniaxial fiber - reinforced composites vary strongly with the direction. However, the extensive experimental data are still lacking to establish quantitatively the angular dependence of properties with confidence.

The present studies were designed to obtain the experimental data to establish the angular dependence of the properties of a unidirectional glass fiber-reinforced/epoxy composites prepared by hand lay-up technique. A number of specimens were prepared and tested under static tensile load with the fibers oriented at different angles. The stress-strain behaviour of all the specimens was studied. The elastic modulus and the strength of the composites were calculated and compared with the theoretical predictions or the experimental results on similar systems. Fracture behaviour of such specimens was also investigated.

It is recognized that for conventional monolithic materials the material response due to static and dynamic loadings may be appreciably different. For composite materials such difference in response becomes further pronounced. Further the particular type of loading appears extremely important in classifying the material response. The impact strength of a material is defined as the energy required for fracture across unit cross-section during high speed loading. It gives a measure of the ability of the material to withstand impact loading and is important since articles are frequently subjected to such loading during service. Many types of impact tests have been devised but the most widely used is the Charpy Impact Test.

Wambech et al [9] have examined the fracture behaviour of glass bead filled polyphenyl oxide (PPO) composites. The addition of glass beads tends to reduce the plane strain fracture toughness. Improvement of adhesion between the beads and polymer further decreases the fracture toughness. Sahu and Broutman [10] have studied the fracture behaviour of epoxy and polyster filled with glass spheres coated with different coating agents. Their results are also in agreement with the results of Wambech et al. Griffith and Holloway [11] have employed a double cantilever beam
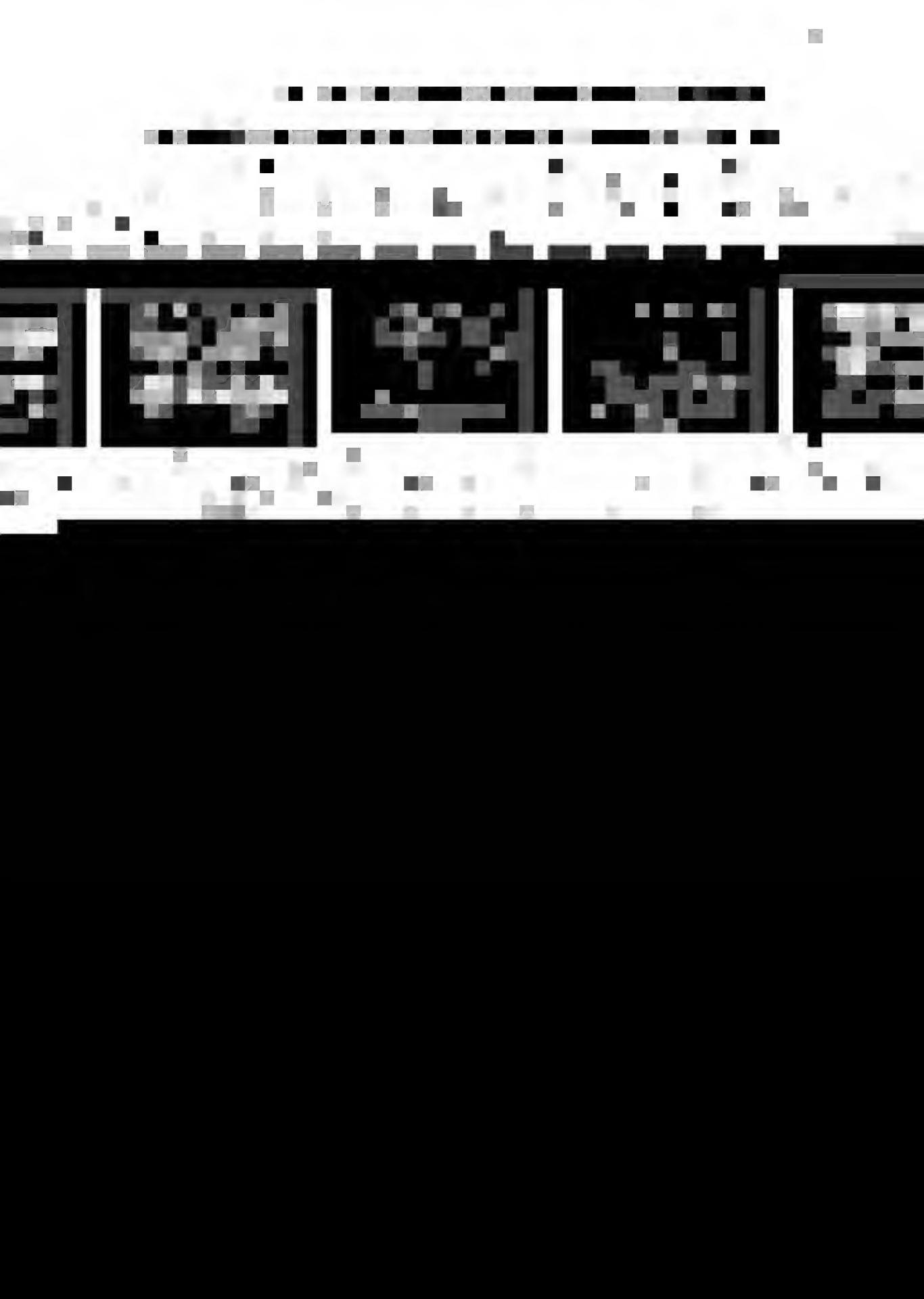
technique to measure the fracture energy of a series of cured epoxy resins. Ellis and Harris [12] used a range of testing techniques to investigate how the measured work of fracture of unidirectionally reinforced carbon fiber/epoxy composites changes with various specimens and test variables. The types of specimens employed included both notched and unnotched specimens. The measured work of fracture was observed to be independent of specimen width and shows slight dependence on notch root radius and test speed. More significant variations occur with orientation, specimen height and notch depth.

Williams et al [13] have studied the fracture behaviour of short fiber and long fiber reinforced composites with notched and unnotched specimens. The fracture energy of these composites have been found to be controlled by the fiber length, fiber volume fraction, effective fiber diameter, fiber tensile strength and the coefficient of friction during fiber pull-out from the matrix. The matrix toughness on the other hand has no effect at all for the composites containing fibers randomly oriented in two dimensions. They further indicate that the unnotched impact strength values and notched impact strength values may be equal to each other.

The angular dependence of impact strength was investigated in the present studies by performing impact tests on unnotched specimens. Two series of tests were carried out. In one of the series the impact load was applied normal to the plane of the composite plates and in the second series the impact load was inplane of the plate. A number of specimens with different fiber orientations were tested on a Mini Charpy Impact Testing Machine. Thus the energy for fracture of specimens with different fiber orientations was obtained. After fracture the specimens were carefully examined to investigate the possible mode of fracture.
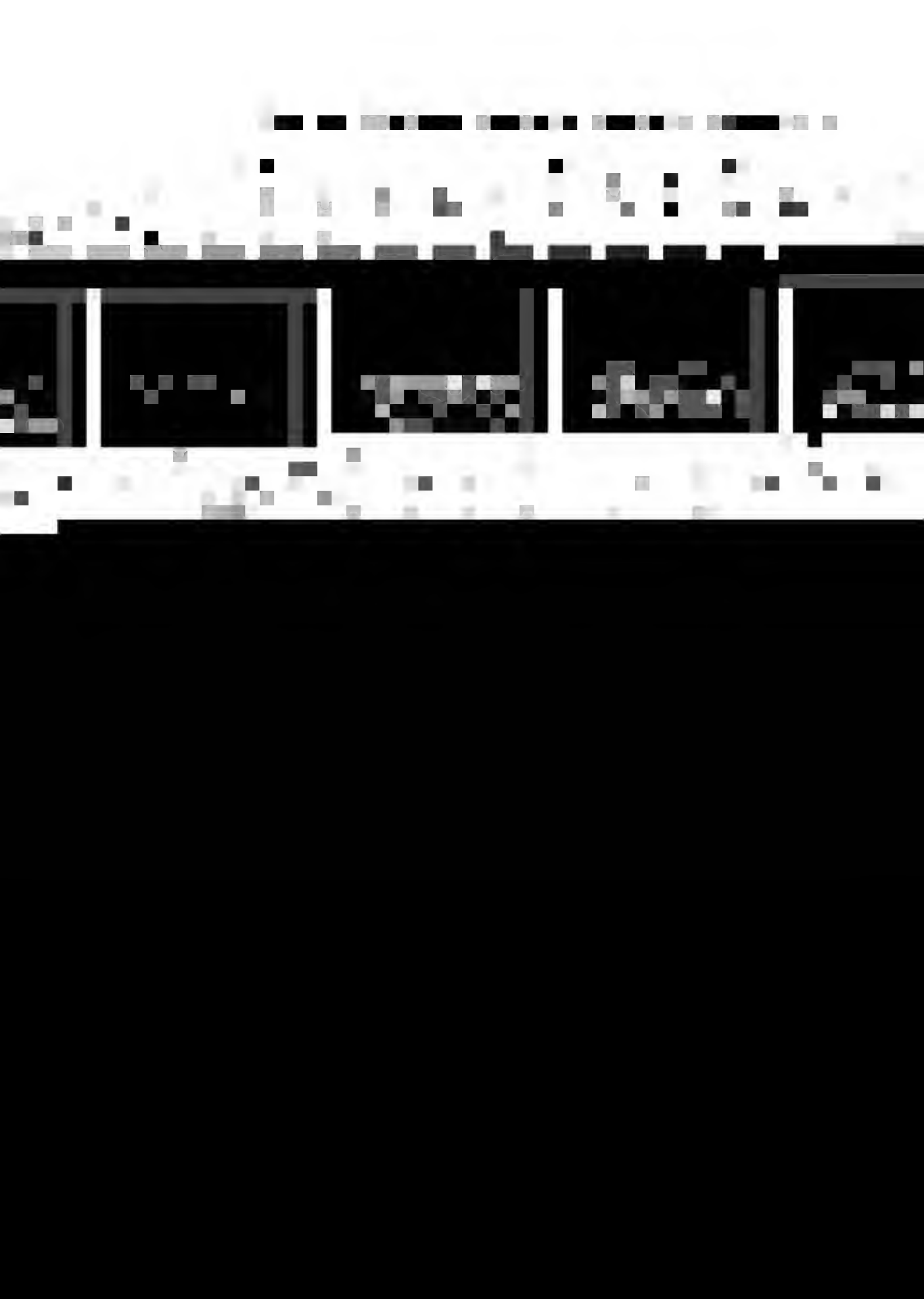
EXPERIMENTAL PROCEDURE

Material Description

Fiber reinforced plastics are one of the oldest and currently most widely used forms of composite materials. Thermosetting plastics were the first to be used with glass reinforcement and today are primarily reinforced by continuous filaments available in the form of fabric, roving, or continuous mats to form high strength materials. The epoxy resins (a thermosetting plastic) make an excellent matrix material because of their versatility, good handling characteristics, low shrinkage, excellent adhesive properties including toughness. The glass fibers are very effective reinforcements because of their high strength and modulus compared to the epoxy resins. Further, since the density of glass is relatively low $(2.54 \text{ gm/cm}^3$ for "E" glass), the strength to weight and modulus to weight ratios of glass-fiber are high, which is of special importance for aerospace and transportation applications.

Present studies were carried out using the epoxy resins as the matrix material and the continuous glass fibers as the reinforcement. Two grades of epoxy resins, manufactured by the CIBA-GEIGY of India Ltd and marketted with the trade name of Araldite, were employed
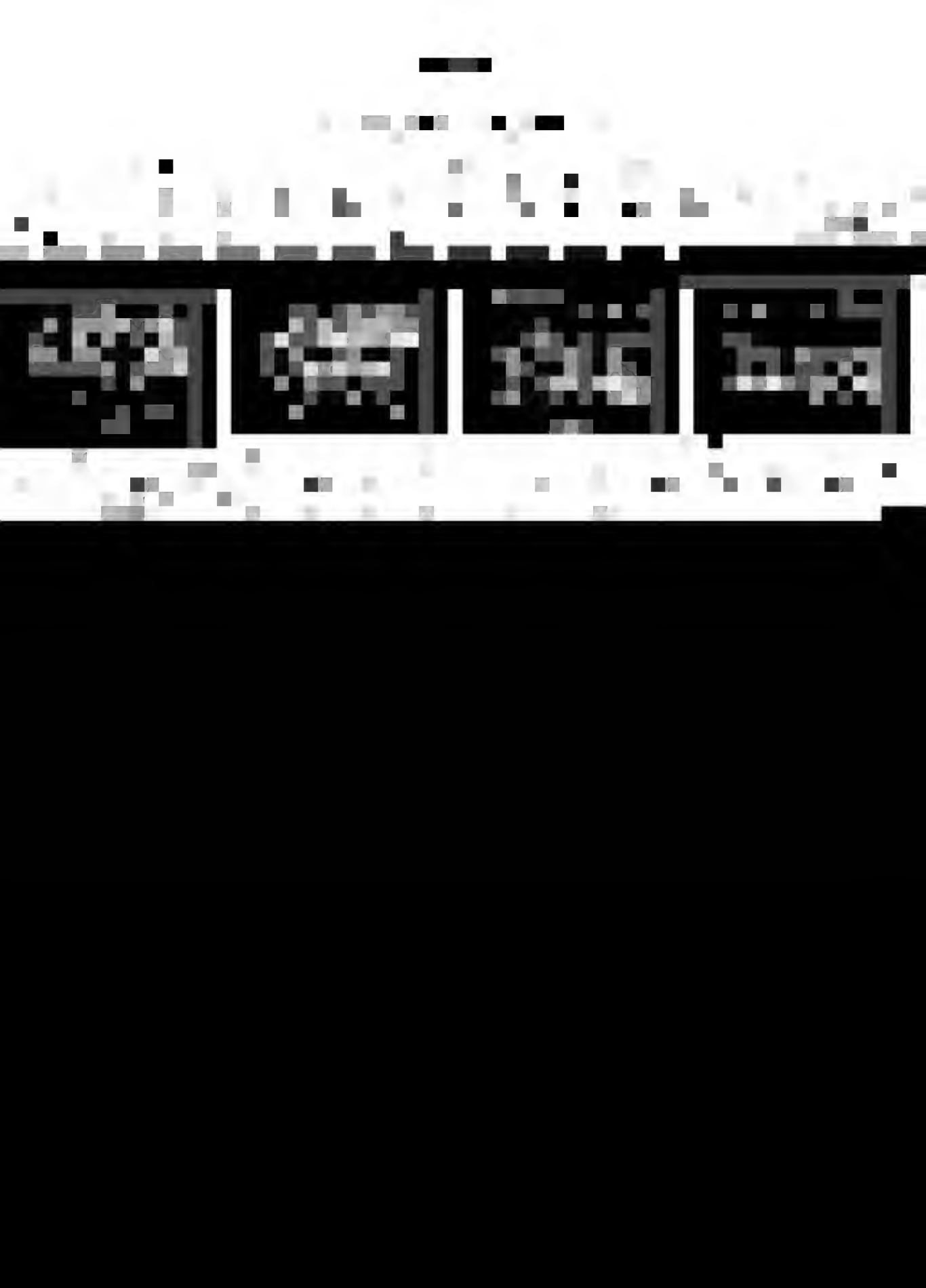
to study the tensile and impact characteristics of the composites. Aliphatic amines were used as the curing agent for both the resins. The percentage (by weight) of curing agent can be varied according to the pot life required. Lower percentage of curing agent was used to have prolonged pot-life. As is indicated later prolonged pot life is essential when the composites are to be made by hand lay-up techniques.

The continuous 'E' - glass fibers were used as the reinforcement to the epoxy matrix. The continuous fibers were wound on a frame from a roving. These glass fibers are a product of the Fiberglass Pilkington Ltd. of India.

Description of the Mould

The mould was made of perspex sheets. Two perspex sheets of suitable size were taken. A rubber lining 25 mm wide and 3.5 mm thick was placed between the perspex sheets on their three sides. The perspex sheets and the rubber liner were then tightened together by means of the nuts and bolts placed through the aligned holes made for the purpose. This makes a closed mould having a side opening only as shown in Fig. 1. The rubber lining acts as a spacer to provide a desired thickness to the composite plates. Rubber lining is preferred as the spacer over the metallic ones as it

provides better sealing of the mould. Several of such moulds were prepared.

Rectangular frames were made of 14 SWG M.S. wire. Size of the frame was such that it could be easily introduced into the mould through the side opening. Continuous glass fibers from a roving are wound closely on the frame. Every care is taken to see that all the fibers are parallel. This frame then becomes ready to be introduced into the resin bath.

Preparation of Composite Plates

Pre-determined quantities of the resin and the curing agent were weighed in separate containers. The resin was heated to about 80 $^{\circ}$C and then allowed to cool. The heating re-conditions the resin stored for a long time and helps remove air bubbles. The curing agent was added to the resin when its temperature dropped to almost the room-temperature. Curing agent was mixed with the resin by stirring the whole mass slowly with a spatula for about two minutes. Due care was taken to avoid any entrapment of the air in the process. For this purpose, stirring was done very slowly and the spatula was not allowed to have any contact with the air.

The mixture was then slowly and carefully poured down the wall of the mould kept ready for the

purpose. The frame on which the fibers were already wound, was then introduced slowly into the mould containing the resin-curing agent mixture. The complete immersion of the frame into the mould was achieved in about 25 to 30 minutes. The mould was then kept for curing at room temperature in the vertical position for 48 hours. A photograph of the mould with resin and fibers in position has been shown in Fig. 1.

A number of methods for making these composite plates were tried before finally opting for the above method. The methods tried included the use of an open mould and using a vacuum chamber to remove air bubbles. However, the method finally adopted produced the most uniform and voidless plates.

Uniformity among the composite plates was duly checked by determining the glass content of the specimens after testing them in tension or under impact loading. The glass content was determined by means of a burn-out test by burning the epoxy resin off in a muffle furnace at 900 $^{\circ}$C for about 6 hours. The glass content thus obtained for 10 specimens taken from different plates were 8.3, 8.4, 8.75, 10.2, 9.3, 8.53, 8.97, 8.87, 10.35, 9.37 percent. It is clearly indicated by only the small variations in the glass contents of various plates that the plates made were more or less uniform in properties. For the purpose of calculations,
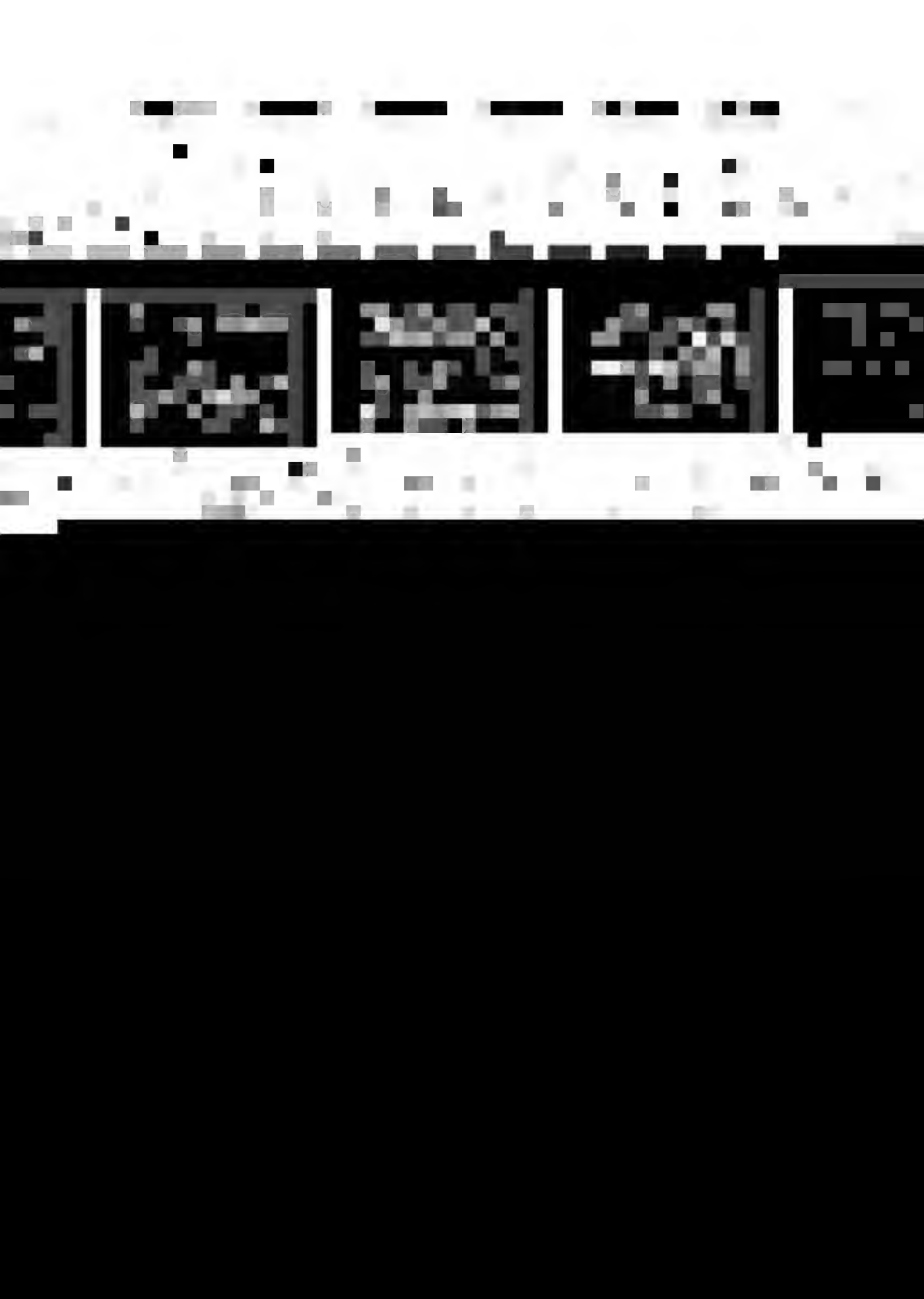
average value of the glass content was taken to be
9.1 percent.

Specimen Preparation

The completely cured composite plates were
cut into the blanks on a band saw. These blanks were
cut in such a manner that the fibers, in the finally
machined specimens were inclined to the axis of load-
ing by a given angle. These blanks were machined to an
ASTM standard (ASTM : D-638 -164 T, Fig. 2a) for a
tensile test specimen. The final dimensions were obtain-
ed by machining the specimens with the help of a meta-
llic template on a high speed routing machine. This
routing machine runs at about 45,000 r.p.m. and has an
end mill cutter for cutting the glass reinforced
composites.

It was decided to use the unnotched specimens
for the Charpy Impact Test. The rectangular specimens
of the size shown in Fig. 2b were sufficient for the
purpose. And as in the case of tensile specimens, the
fibers in the specimens were inclined to the edge of
the specimen by a given angle.

Experimental Procedure

The specimens were tested in tension on an
Instron machine with the load applied across the speci-
men ends using wedge-acting grips. A cross-head speed

of 0.2 cm per minute was used and the load vs elonga-
tion curve was directly recorded on the Instron X-Y
recorder. Atleast 5 specimens were tested for a given
orientation of the fibers to the loading axis.

The Charpy Impact Tests were performed on
a Mini Charpy Impact Testing Machine having a maximum
energy of the hammer equal to 0.4 Kgm. The energy
absorbed in the impact of specimen could be read to
the accuracy of 0.005 Kgm.

Two series of Impact Tests were carried out.
In the first series the impact load was applied per-
pendicular to the plane of the composite plate where
as in the second series the load was in the plane of
the plate. However, in both the cases, the load was
in a plane perpendicular to the longitudinal axis of
the specimen. And as has been indicated earlier the
fibers were oriented at different angles to the longi-
tudinal axis. In this case also atleast five specimens
were tested for a given orientation of the fibres to
the longitudinal axis.

CHAPTER III

RESULTS AND DISCUSSION

Stress-Strain Behaviour

The stress-strain curve for the epoxy resin (without any glass-fibers) has been shown in Fig. 3. It can be seen that the curve is initially linear and after a strain of about 0.7 per cent it becomes non - linear. The maximum load was 90 Kg and the load at fracture was also the same. This stress-strain behaviour of the epoxy is as expected [14] .

Tensile tests were performed on the specimens with the fibers inclined at angles of 0, 10, 20, 30, 45, 60, 70, 80 and 90 degrees with the loading axis. Atleast five specimens were tested for each fiber - orientation. In all the cases the load elongation curves were directly recorded on the Instron X - Y recorder. The representative load - elongation curves for each orientation have been shown in Figures 4 to 6. It may be pointed out that the variation in load elong- ation curve can be taken to be the variation in stress- strain curve of the specimens, because the nominal dimensions of the specimens were same in all the cases.

Figure 4 shows that the stress - strain curve for the tensile specimen with all the fibers parallel to the direction of the load is non - linear. However,

it can be very closely approximated by two straight lines. These straight lines intersect at a strain of about 1.8 per cent. The initial and final moduli were found to be about 230 Kg/mm^2 and 170 Kg/mm^2 respectively. This change in slope may be due to extensive local plastic deformations of the matrix and fracture of some of the fibers at their weak cross-sections. This behaviour of the composite has been predicted by Agarwal and Broutman [15]

Figures 5 and 6 show that load - elongation curves for all cases of different fiber - orientations with the loading axes are non linear. The initial linear portion of the curves becomes smaller as the angle between the fibers and the loading axis increases. In the cases of fiber - orientations other than zero degree the load - elongation curves cannot be approximated by two straight lines as was done in the case of specimens with all the fibers parallel to the loading axis. This non - linear behaviour is due to the increased importance of the matrix in the unidirectionally reinforced fibrous composites when loading is not parallel to the direction of the fibers. This will be further discussed later on along with the fracture behaviour of the specimens.

The initial slope of the curve was calculated for all the specimens and taken to represent the

initial modulus of the composite. The moduli values for all the specimens have been given in Table - 1.

The modulus of Elasticity of the composites with all the fibers parallel to the direction of loading has been obtained as about 230 Kg/mm^2. The modulus of unidirectional fibrous composites can be calculated quite accurately by the "rule of mixtures"[1] as follows :

$$E_c = E_f \cdot V_f + E_m (1 - V_f) \qquad (1)$$

By taking $E_m = 55$ Kg/mm^2 and $E_f = 6,800$ Kg/mm^2 (approx. 10×10^6 psi), $V_f = 0.091$, we get $E_c = 664$ $Kg./mm^2$.

This modulus is higher than the one experimentally obtained by a factor of nearly three. In the absence of any relevant information from the manufacturer about the finish, it is suspected that the finish on glass - fibers was such that a good chemical bonding between the fibers and the matrix did not exist. It has been predicted theoretically by Agarwal and Broutman [2,3] that a weak interface, in which a relative slip between the fibers and the matrix is permissible, can lower the modulus of the composite by an order of magnitude compared to what will be obtained if the good bonding between fibers and the matrix existed. It has been reported [16] that in case of a composite material made with 60 percent by volume of glass

fibers having a volan finish, show an elastic modulus of 2,000 Kg/mm^2 which would mean that if the V_f were 10% the E_c would be 270 Kg/mm^2. The results favourably compare with the present experimental results. The slight discrepancy in the results may be attributed to the fabrication technique. It was indicated by Goggin [6] that the composite made by hand lay-up technique may show a 25% lower composite modulus. The fiber mis-- alignment and their deterioration due to the handling may result in further reduction in the modulus [8]. The results of the moduli of the composites have been plotted as a function of the angle of orientation in Figure 7. The curve shows a trend similar to the expected one [16].

Knibbs and Morris [8] have shown that the anisotropic behaviour of the composite can be represen- ted by the angular dependence of the elastic modulus in the following form :

$$\frac{E_o \, / \, E_\theta - 1}{Sin^2 \, \theta} \; = \; A - B \; Sin^2 \, \theta \qquad\qquad (2)$$

$$\text{where} \quad A \; = \; \frac{\frac{1}{G_{12}} + \frac{2 \nu_{12}}{E_{22}} - \frac{2}{E_{22}}}{\frac{1}{E_{22}}}$$

$$B \; = \; \frac{\frac{1}{G_{12}} + \frac{2 \nu_{12}}{E_{22}} - \frac{1}{E_{22}} - \frac{1}{E_{11}}}{\frac{1}{E_{22}}}$$

Figure 8 shows a graph of $\dfrac{E_o/E_\theta - 1}{\sin^2\theta}$ Vs $\sin^2\theta$ from the calculated values of E_θ. The data show a straight line variation of the parameters indicating a good agreement between the experimental data with equation (2).

Tensile Strength

The ultimate tensile strength of the specimens was calculated from the knowledge of the maximum load carried by the specimen. The maximum load was found to be equal to the fracture load for all the specimens. The maximum load divided by the initial area of cross-section gives the ultimate tensile strength. The values of the tensile strength of all the specimens have also been reported in Table - 1.

The tensile strength of the epoxy resin has been obtained to be 2.0 Kg/mm^2. The tensile strength of the composite materials with all the fibers parallel to the direction of loading is 12.2 Kg/mm^2. An estimate of the tensile strength of the unidirectional longitudinal fibrous composites can also be made by the "rule of mixtures." Taking the matrix strength as 2.0 Kg/mm^2 and the fiber strength as 140 Kg/mm^2 the composite strength is obtained to be 14.4 Kg/mm^2 by rule of mixtures. The slightly lower value of tensile strength obtained experimentally can be attributed to the fabrication technique of the composites. Breaking of

some of the fibers in the handling during fabrication certainly lowers the strength of the composites. Gill [17] has pointed out that twist in the reinforcement, even though it may involve only small percentage of fibers, is detrimental because the twisted fibers do not contribute to the strength fully but do give uneven resin distribution. In the hand lay-up technique, the twisting of fibers coming from the rovings at certain places is almost unavoidable.

The strength of the composites has been plotted as a function of the fiber orientation in Figure 9. It may be noted that the strength of the composite drops very sharply as the angle between the fibers and the loading axis increases. However, the drop in strength is reduced as the angle between the two exceeds 45°. An estimate of the strength can be made by various failure theories for the composites [18] . One of the more widely accepted theories is the maximum work theory which predicts the strength of the composites as follows :

$$\frac{1}{\sigma_f^2} = \frac{\cos^4 \theta}{X^2} + (\frac{1}{S^2} - \frac{1}{X^2}) \cos^2 \theta \sin^2 \theta$$
$$+ \frac{\sin^4 \theta}{Y^2} \qquad (3)$$

where X and Y are the normal strengths in the two directions, S. is the shear strength in coordinate directions

and σ_1 the strength of the composite in the direction
of the load.

For comparing the experimental results with
equation (3), X has been taken as the strength with
fibers parallel to the loading axis and Y as that with
all the fibers perpendicular to the loading axis. S has
been calculated from equation (3) from the knowledge of
the strength of the composite for a fiber orientation
of 30 degree. Predictions of equation (3) have also
been plotted in Figure 9. The experimental and the
theoretical results agree quite favourably.

Impact Strength

It was decided to use unnotched specimens for
impact tests because the introduction of glass fibers
in the epoxy matrix makes it brittle. Thus the energy
absorbed by the notched specimens may be very low and
it may become difficult to distinguish between the ener-
gies absorbed by the specimens with different fiber
orientations. Sahu [10] in his investigation with the
fracture of composite materials has recommended for the
use of unnotched specimens for impact tests. Further it
was indicated by Ellis and Harris [12] that the samples
of very different heights and different notch depths
exhibit similar works of fracture provided their uncrac-
ked heights are the same. William, Allen and Kaufman [13]

have indicated that the fibers distribute the stress away from the notch, thus eliminating the effect of the notch entirely. This essentially means that the unnotched impact strength should be equal to the notched impact strength. Their experimental results support the above theory.

In the present study unnotched impact strength was determined for the specimens with the fibers oriented at different angles with the longitudinal axis. In one series of tests the specimens were placed on the thickness of the specimens so that the impact load was applied perpendicular to the plane of the plate. In the second set the specimens were kept on the width so that the impact load was parallel to the plane of the plate.

The Tables 2 and 3 show impact energy for all the specimens in the two series of tests. It may be noted that the energy required for the fracture of specimens with a particular fiber orientation is smaller in the case where impact load is perpendicular to the plane of the plate. This behaviour should be expected because the distribution of fibers across width is more uniform compared to that across the thickness. The fibers are essentially concentrated at the outermost layers of the plate. This should result in a lower flexural strength as well as the lower impact energy

when the load is perpendicular to the plane of the plate.

The results of impact energies have been plotted as a function of angle between the fibers and the longitudinal axis of the specimen in Figure 10. These curves show a trend similar to that obtained by Ellis and Harris [12] for carbon-fiber/epoxy composites. In both the cases it has been observed that the energy required for fracture of composites with all the fibers perpendicular to the load is much higher, compared to that with the specimens of epoxy alone. However, this impact energy drops very rapidly as the angle between the fibers and the longitudinal axis increases. This drop in the energy is reduced as the angle between the fibers and the longitudinal axis exceeds about 30 degrees. At this fiber-orientation the impact energy of the composite material has been observed to be approximately equal to the corresponding energy for specimens of epoxy only. The drop in impact energy to value less than that for the epoxy alone is due to the fact that fibers produce stress concentrations but do not effectively restrain the propagation of the crack.

Failure Mechanism

The specimens subjected to tensile tests were carefully observed during the testing and were examined

place. Failure of the epoxy specimens without any
glass - fibers takes place along a plane perpendicular
to the loading axis. The fracture surface is quite
smooth in appearance indicating that brittle fracture
took place. Figure 11 shows the specimens of epoxy
which failed in a tensile test.

It is well known that in a unidirectional
glass fiber - reinforced plastics the major portion of
the load is carried by the fibers, especially so at the
higher volume fraction of the glass fibers. As the
load parallel to the direction of the fibers increases,
some fibers break at their weak cross - sections. Break-
ing of the fibers produces local stress - concentration
and slightly increases the load on the adjacent fibers.
The high stresses in the matrix near the broken fiber
may be relieved by the plastic deformation of the matrix.
However, in case of a brittle matrix this may become the
initiation of the failure of the matrix. In some cases
the high stresses produced due to the breaking of the
fibers may cause a complete debonding of the fibers from
the matrix. In this case the debonded fiber ceases to
carry any part of the load thereby increasing the
stresses on the adjacent fibers. As the sites of the
broken fibers increase the load on the unbroken fibers
increases proportionately. The process of breaking of

individual fibers at different sections is completely random. When sufficient number of fibers have broken at a particular section, that particular section may be weakened enough, not to be able to support the load thereby causing the complete fracture of the composite. In the present investigation this mode of fracture was observed for the specimens with fibers parallel to the direction of the load. Figure 12 shows the photographs of the fractured specimens with all the fibers parallel to the loading direction. It is clearly demonstrated that the propagation of the crack was completely random. Only very small amount of debonding has been observed which actually takes place in the final stages of the fracture.

Figure 13 shows the fractured specimens with the fibers oriented at 10 degree to the loading direction. It can be seen that the fracture initiated by breaking some of the fibers near the surface. The fracture propagates by delamination of the fibers from the matrix and also by breaking some more fibers adjacent to the debonded fibers. However, it may be noted that the debonding of the fibers is not extensive i.e. the debonding takes place only adjacent to the fractured surface. The fiber pull-out was also very small indicating a good bonding between the fibers and the matrix.

Figure 14 shows the fractured specimens with the fibers oriented at more than 10 degrees to the loading direction. Specimens with fibers oriented at 20 degrees show breaking of some fibers. However, the propagation of fracture appears to be completely due to the delamination process and takes place along the fibers i.e. the fracture surface is also inclined nearly 20 degree to the loading direction. In the specimens with the fibers oriented at angles 30 degree or more, breaking of the fibers was not observed, the fracture once initiated at some weak section of specimen propagates along the direction of the fibers. It can be noted that the fracture surface is inclined to the loading direction by the same angle as the fibers. Similar fracture behaviour has been observed by Pipes [19] while working with the boron - epoxy system.

The photographs of the fractured specimens tested under impact loads have been shown in Figures 15 and 16. Figure 15 shows the specimens which were subjected to the impact loads perpendicular to the plane of the plate. The specimens of epoxy without any glass-fibers broke into two pieces showing a square fracture. The specimens with fiber orientations of 0, 10, 20, 30 and 45 degrees did not separate in two pieces under the impact loads. Extensive delamination and the fiber pull-outs have been observed in these cases. The specimens with the fibers oriented at 60, 70, 80 and 90 degrees

have generally broken into two pieces. The fracture
surface is generally parallel to the direction of the
fibers.

Fracture of the specimens subjected to the
in-plane impact loads has been shown in Figure 16. In
this case the epoxy specimens broke into several pieces
of which some could not be located. The specimens with
the fibers oriented at 0 and 10 degrees did not separate
into two pieces in this case also like the ones when the
impact load was perpendicular to the plane of the plate.
The specimens with the fibers oriented at 20, 30 and
45 degrees generally separated into two pieces except
for some common unbroken fibers between the two pieces.
In these three cases the fracture generally took place
along the direction of the fibers. The specimens with
fibers oriented at 60, 70, 80 and 90 degrees were com-
pletely separated in two pieces and the fracture took
place along the directions of the fiber as can be seen
in the figure.

CHAPTER IV

CONCLUSION

Tensile tests and Charpy impact tests have been performed on unidirectional continuous glass fiber reinforced epoxy composites prepared by hand lay - up technique.

Tensile specimens of composites with the fibers oriented at 0, 10, 20, 30, 45, 60, 70, 80 and 90 degrees to the axis of load were tested on an Instron machine at a cross-head speed of 0.2 cm per minute. Atleast five specimens were tested for each fiber orientation.

Load elongation curves were obtained directly on the X - Y recorder of the Instron. These curves have been taken to represent the stress - strain behaviour of the composite. The stress - strain curve of the composite with all the fibers parallel to the loading direction can be very closely approximated by two straight lines with their slopes furnishing the values of initial and final moduli to be equal to 230 Kg/mm^2 and 170 Kg/mm^2 respectively. This change in slope has been attributed to the local plastic deformation of the matrix and fracture of some of the fibers at their weak cross-section. In the case of fiber orientations other than zero degree, the load - elongation curve is

more non-linear and cannot be approximated by two
straight lines. The initial linear portion of the curve
decreases as the angle of orientation increases. This
non-linear behaviour indicates that now the matrix is
playing a major role in the deformation of the composite.
The initial modulus of the composite has been calcula-
ted for the specimens with different orientations. The
moduli values have been compared with the theoretical
predictions and the results of other investigators with
the similar systems. The results generally show a good
agreement. The hand lay-up technique has been reported
to lower the moduli values. The angular dependence of
moduli has also been established and the results are in
good agreement with those of other investigators.

Tensile strength has been calculated from the
knowledge of the maximum load carried by the specimen.
The strength values have also been compared with the
theoretical calculations such as the "rule of mixtures"
and the predictions of the strength theories of the
composite materials. Here also the results agree quite
favourably.

Impact tests have been performed on unnotched
specimens on a mini Charpy Impact Testing Machine. Here
also the specimens had the fibers oriented at different
angles to the longitudinal axis. Two series of tests
have been performed. In one series the impact load is

applied perpendicular to the plane of the plate and in the other series in the plane of the plate. The impact energy has been found to be lower in the case where impact load is perpendicular to the plane of the plate which is an expected behaviour, because of the distribution of fibers being less uniform across the thickness of the plate. However, in both the cases the impact energy drops as the angle of orientation of fibers to the longitudinal axis increases. This trend is similar to that obtained for carbon/epoxy composites by other investigators. It has been observed that the Impact Energy of the specimens with fibers oriented at 30 degree to the longitudinal axis is the same as that for specimens of epoxy without any glass fibers.

Fracture behaviour of the composites has been studied for the tensile as well as the impact loading. The fracture of specimens with all the fibers parallel to the tensile load occurs in a random fashion i.e. the fracture is not restricted to one cross-section. Small amount of debonding is also observed which actually takes place in the final stages of the fracture. The specimens with fibers oriented at 30 degrees or more fracture by the delamination process along the direction of the fibers. However, the specimens with fibers oriented at 10 degree and 20 degree fail through a combination of fiber breaking, matrix cracking and fiber matrix debonding.

The specimens subjected to impact loads
perpendicular to the plane of the plate show two kinds
of fracture-behaviour. The specimens with fibers orien-
ted at angles between 0 and 45 degrees to the longitu-
dinal axis show an extensive delamination and fiber
pull out and the specimens actually do not break in two
pieces. This behaviour has also been attributed to the
non-uniform fiber-distribution across the thickness.
The fracture of the specimens with the fibers oriented
at 60 degrees or more takes place along the direction
of the fibers and specimen is separated into two pieces.
This behaviour indicates an increased role of the matrix
in the fracture of composites.

The specimens under in-plane impact load show
a more uniform trend of fracture for all the fiber
orientations. The specimens oriented at 20 to 90 degrees
with the longitudinal axis are generally seperated into
two pieces, though some common unbroken fibers have been
observed. However, the specimens with fibers oriented
at 0 and 10 degrees to the longitudinal axis do not
separate into two pieces due to high impact energy re-
quired for the fracture.

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TABLE 1

RESULTS OF MODULI AND TENSILE STRENGTH OF THE COMPOSITES

Orientation	Sample No.	Cross-Section (Sq.mm)	U.T. Load (Kg.)	U.T. Strength (Kg./mm)	Mean U.T($_1$) (Kg/mm^2)	Young's Modulus (E) (Kg/mm^2)	Mean E (Kg/mm^2)
1	2	3	4	5	6	7	8
0°	1	44.49	590	12.97		241.7	
	2	45.33	580	12.79		242.7	
	3	45.28	240	11.92		243.0	
	4	45.24	510	11.27	12.165	212.2	229.1
	5	45.33	540	11.91		211.8	
	6	45.87	660	14.38		239.7	
	7	43.60	500	11.47		220.2	
	8	43.33	460	10.62		221.6	
10°	1	43.79	315	7.192		185.7	
	2	44.21	360	8.143		191.4	
	3	44.41	410	9.233		190.5	
	4	44.96	430	9.566	8.541	195.7	190.6
	5	44.87	385	8.580		188.5	
	6	44.02	360	8.177		192.3	
	7	44.41	395	8.894		190.5	
20°	1	45.20	260	5.753		168.7	
	2	45.40	265	5.835		168.0	
	3	45.10	255	5.653	6.034	169.1	167.5
	4	46.00	300	6.519		165.8	
	5	46.00	295	6.412		165.8	
30°	1	45.70	175	3.829		139.1	
	2	46.00	190	4.130		138.1	
	3	45.80	180	3.930		138.8	
	4	45.80	182	3.974	3.755	138.8	132.3
	5	45.30	162.5	3.591		126.3	
	6	45.60	170	3.727		125.4	
	7	45.70	162.5	3.559		125.6	
	8	45.30	150	3.311		126.3	
45°	1	43.80	76	1.735		78.3	
	2	44.00	74	1.682		78.00	
	3	44.00	82	1.863		78.00	
	4	44.00	78	1.772	1.757	78.00	78.23
	5	43.85	76	1.733		78.27	
	6	43.85	82	1.869		78.27	
	7	43.60	70	1.607		78.72	

(Continued)

TABLE 1 (Continued)

1	2	3	4	5	6	7	8
60°	1	45.00	93	2.066		90.80	
	2	44.36	88	1.984		99.80	
	3	45.08	94	2.084		97.61	
	4	45.71	100	2.188	2.120	96.26	100.29
	5	45.39	94	2.070		105.00	
	6	46.24	104	2.249		103.00	
	7	44.98	92	2.046		105.90	
	8	45.71	104	2.275		104.20	
70°	1	45.00	83	1.845		63.55	
	2	45.08	85	1.886		70.41	
	3	44.98	83	1.845		66.92	
	4	45.39	85	1.873		63.01	
	5	45.71	87	1.903	1.895	62.58	63.23
	6	47.53	90	1.893		60.17	
	7	45.19	88	1.947		63.28	
	8	47.86	94	1.964		59.77	
	9	46.85	91	1.941		61.02	
	10	46.45	86	1.851		61.58	
80°	1	45.19	67	1.483		63.28	
	2	46.67	72	1.543		61.42	
	3	46.08	69	1.497		70.63	
	4	46.10	70	1.518	1.469	62.04	65.62
	5	46.67	73	1.564		61.32	
	6	45.13	63	1.396		70.41	
	7	45.10	58	1.286		70.41	
90°	1	43.34	70	1.615		54.99	
	2	43.42	76	1.750		54.89	
	3	43.82	80	1.826		54.39	
	4	43.96	82	1.865	1.822	54.21	54.46
	5	43.76	80	1.828		54.46	
	6	44.21	86	1.945		53.92	
	7	43.82	88	1.927		54.39	
ARALDITE LY 553 WITH 7% CURING AGENT HY951	1	44.17	88	1.993		53.96	
	2	44.88	91	2.027		64.89	
	3	44.88	89	1.983	2.035	63.72	59.34
	4	43.96	92	2.092		57.57	
	5	43.96	91.5	2.081		56.57	
ARALDITE CY 230 WITH 8% CURING AGENT HY951	1	43.45	132	3.038		109.1	
	2	43.67	136	3.107		109.7	
	3	43.88	140	3.190	3.105	108.6	108.9
	4	44.08	136	3.084		109.1	
	5	43.70	136	3.107		108.1	

TABLE 2

MINI CHARPY IMPACT TEST RESULTS OF THE COMPOSITES
(LOAD PERPENDICULAR TO THE PLANE OF THE PLATE)

Orientation	Sample No.	Fracture Energy (Kgm.)	Fracture Energy (Kg cm/cm^2)	Mean Fracture Energy (Kg cm/cm^2)
0°	1	0.215	61.43	
	2	0.312	89.43	
	3	0.275	78.57	71.60
	4	0.215	61.43	
	5	0.350	67.14	
10°	1	0.150	42.86	
	2	0.195	55.71	
	3	0.155	44.28	50.28
	4	0.185	52.86	
	5	0.195	55.71	
20°	1	0.125	35.71	
	2	0.130	37.14	
	3	0.113	32.28	34.28
	4	0.132	37.71	
	5	0.100	28.57	
30°	1	0.050	14.29	
	2	0.065	18.57	
	3	0.060	17.14	16.57
	4	0.055	15.71	
	5	0.060	17.14	
45°	1	0.025	7.14	
	2	0.025	7.14	
	3	0.035	10.00	8.28
	4	0.030	8.57	
	5	0.030	8.57	
60°	1	0.025	7.14	
	2	0.024	6.86	
	3	0.020	5.71	6.456
	4	0.025	7.14	
	5	0.019	5.43	

(Continued)

TABLE 2 (Continued)

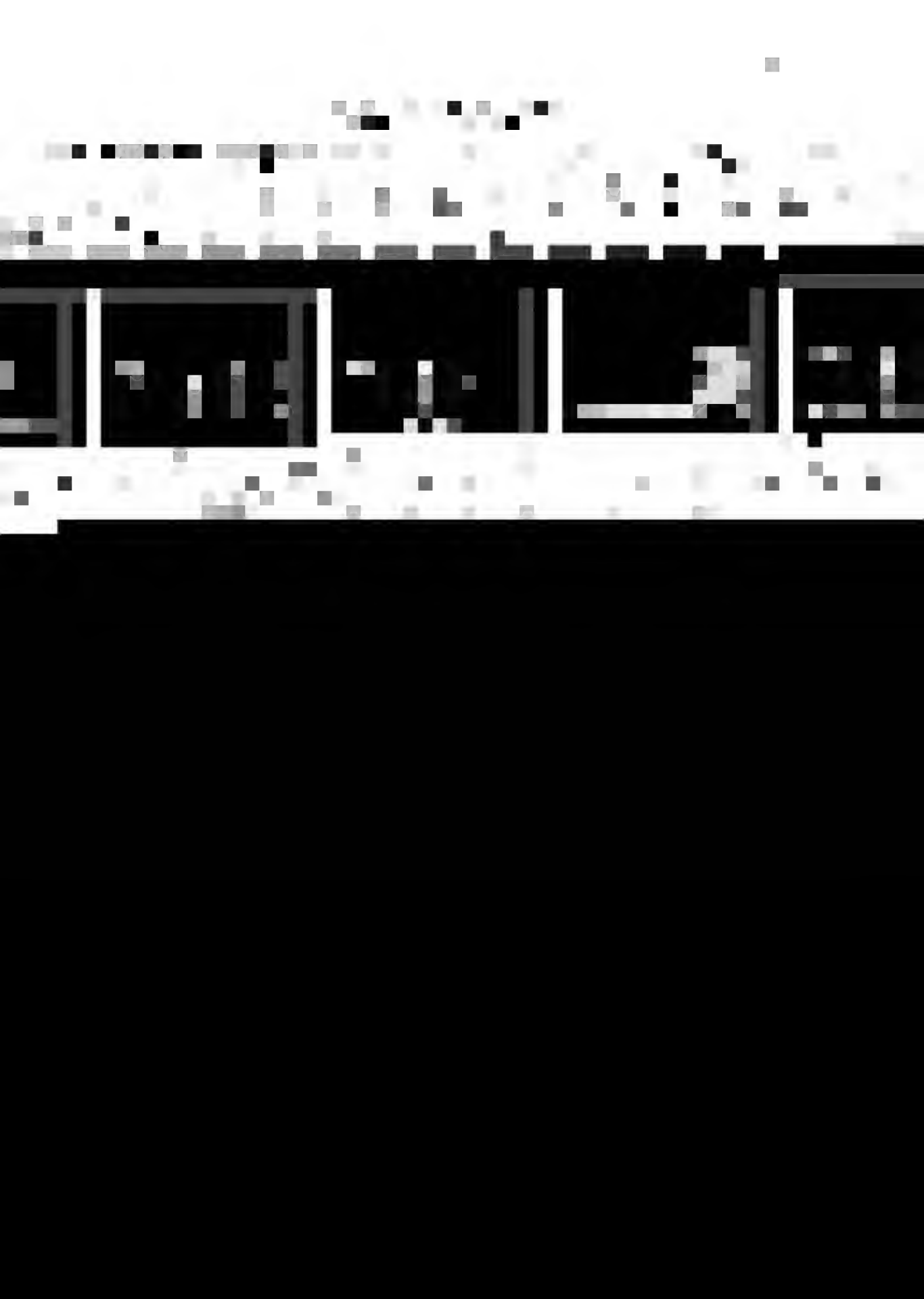| Orientation	Sample No.	Fracture Energy (Kgm.)	Fracture Energy (Kg cm/cm^2)	Mean Fracture Energy (Kg cm/cm^2)
70°	1	0.015	4.29	4.174
	2	0.015	4.29	
	3	0.015	4.29	
	4	0.015	4.29	
	5	0.013	3.71	
80°	1	0.015	4.29	4.140
	2	0.013	3.71	
	3	0.015	4.29	
	4	0.014	4.00	
	5	0.015	4.29	
90°	1	0.012	3.43	3.544
	2	0.015	4.29	
	3	0.010	2.86	
	4	0.012	3.43	
	5	0.013	3.71	
EPOXY ONLY (ARALDITE JY 230 WITH 3% CURING AGENT IY 951)	1	0.040	11.43	16.57
	2	0.060	17.14	
	3	0.090	25.71	
	4	0.050	14.28	
	5	0.050	14.28	

TABLE 3

MINI CHARPY IMPACT TEST RESULTS OF THE COMPOSITES
(LOAD IN PLANE OF THE PLATE)

Orientation	Sample No.	Fracture Energy (Kgm.)	Fracture Energy (Kg cm/cm^2)	Mean Fracture Energy (Kg cm/cm^2)
0°	1	0.380	108.57	
	2	0.320	91.43	
	3	0.390	112.86	
	4	–	–	Sample did not break 100.20
	5	0.350	100.00	
	6	0.360	102.86	
	7	–	–	Sample did not break
	8	0.31	88.57	
	9	–	–	– Do –
	10	0.34	97.14	
10°	1	0.365	104.29	
	2	0.375	107.14	
	3	0.350	100.00	
	4	0.230	65.71	
	5	0.330	94.29	86.86
	6	0.320	91.43	
	7	0.240	68.57	
	8	0.370	77.14	
	9	0.290	82.86	
	10	0.270	77.14	
20°	1	0.095	27.14	
	2	0.150	42.86	
	3	0.120	34.29	
	4	0.105	30.00	
	5	0.095	27.14	39.63
	6	0.200	57.14	
	7	0.230	65.70	
	8	0.130	37.14	
	9	0.120	34.29	
	10	0.135	38.57	
30°	1	0.062	17.72	
	2	0.064	18.29	
	3	0.068	19.43	
	4	0.069	19.71	
	5	0.070	20.00	20.52
	6	0.070	20.00	
	7	0.080	22.86	
	8	0.070	20.00	
	9	0.080	22.86	
	10	0.085	24.28	

(Continued)

TABLE 3 (Continued)

Orientation	Sample No.	Fracture Energy (Kgm.)	Fracture Energy (Kg cm/cm^2)	Mean Fracture Energy (Kg c/c)
45°	1	0.045	12.86	
	2	0.050	14.29	
	3	0.055	15.71	
	4	0.042	12.00	
	5	0.047	13.43	13.53
	6	0.055	15.71	
	7	0.052	14.86	
	8	0.046	13.14	
	9	0.040	11.43	
	10	0.042	12.00	
60°	1	0.039	11.29	
	2	0.034	9.71	
	3	0.032	9.14	
	4	0.040	11.43	
	5	0.036	10.29	10.47
	6	0.033	9.43	
	7	0.036	10.29	
	8	0.040	11.43	
	9	0.045	12.86	
	10	0.031	8.86	
70°	1	0.030	8.57	
	2	0.029	8.29	
	3	0.027	7.71	
	4	0.031	8.86	
	5	0.029	8.29	8.513
	6	0.030	8.57	
	7	0.035	10.00	
	8	0.030	8.57	
	9	0.030	8.57	
	10	0.027	7.71	
80°	1	0.024	6.86	
	2	0.023	6.57	
	3	0.027	7.71	
	4	0.030	8.57	
	5	0.025	7.17	6.830
	6	0.023	6.57	
	7	0.024	6.86	
	8	0.023	6.57	
	9	0.020	5.71	
	10	0.020	5.71	

Orientation	Sample No.	Fracture Energy (Kgm.)	Fracture Energy (Kg cm/cm^2)	Mean Fracture Energy (Kg cm/c
90°	1	0.023	6.57	
	2	0.023	6.57	
	3	0.025	7.17	
	4	0.022	6.28	
	5	0.022	6.28	6.432
	6	0.020	5.71	
	7	0.022	6.28	
	8	0.025	7.17	
	9	0.022	6.29	
	10	0.021	6.00	
EPOXY ONLY (ARALDITE CY 230 WITH 8% CURING AGENT HY 951)	1	0.050	14.29	
	2	0.100	28.57	
	3	0.075	21.43	
	4	0.105	30.00	
	5	0.085	24.28	22.57
	6	0.100	28.57	
	7	0.065	18.57	
	8	0.065	18.57	
	9	0.070	20.00	
	10	0.075	21.43	
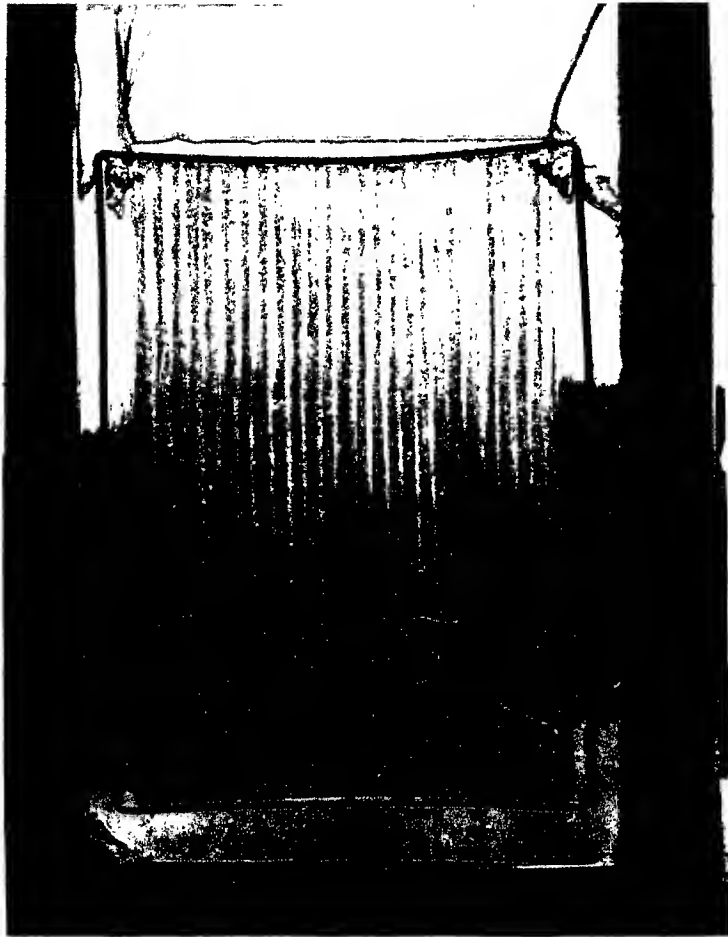
FIG. 1 : Mould with the resin and the fibers wound on a frame.

76

12.7

57.2

165
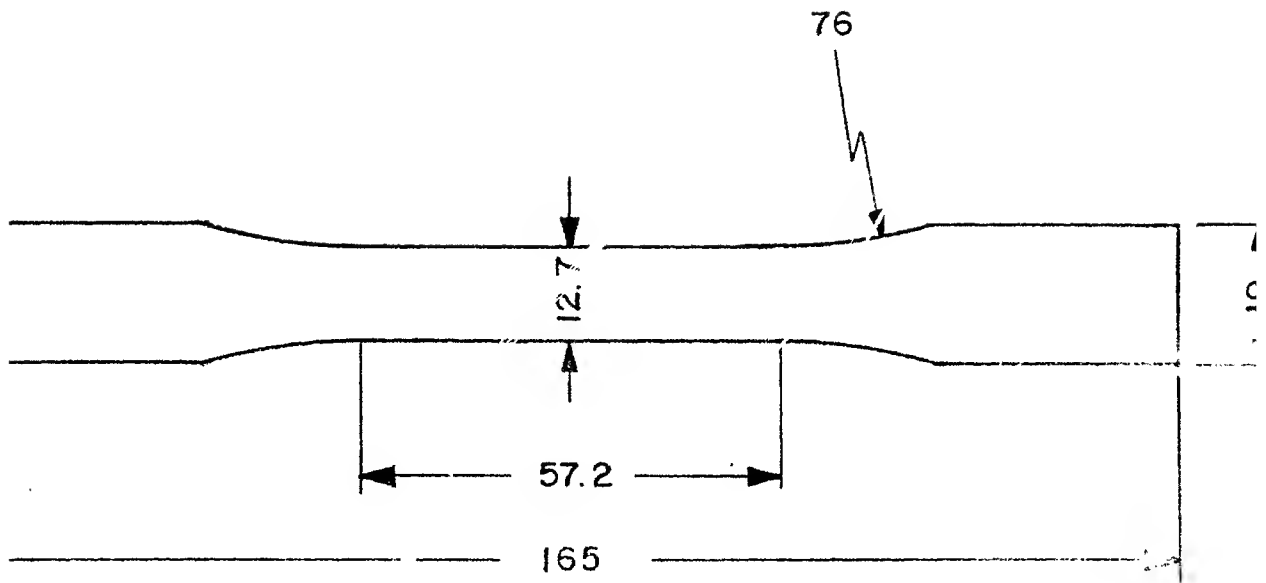
(a) Tensile Specimen (ASTM D638-64T)

10

55
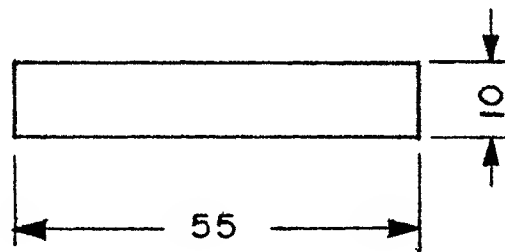
(b) Unnotched Charpy Impact Specimen

Thickness Of Specimens = 3.5
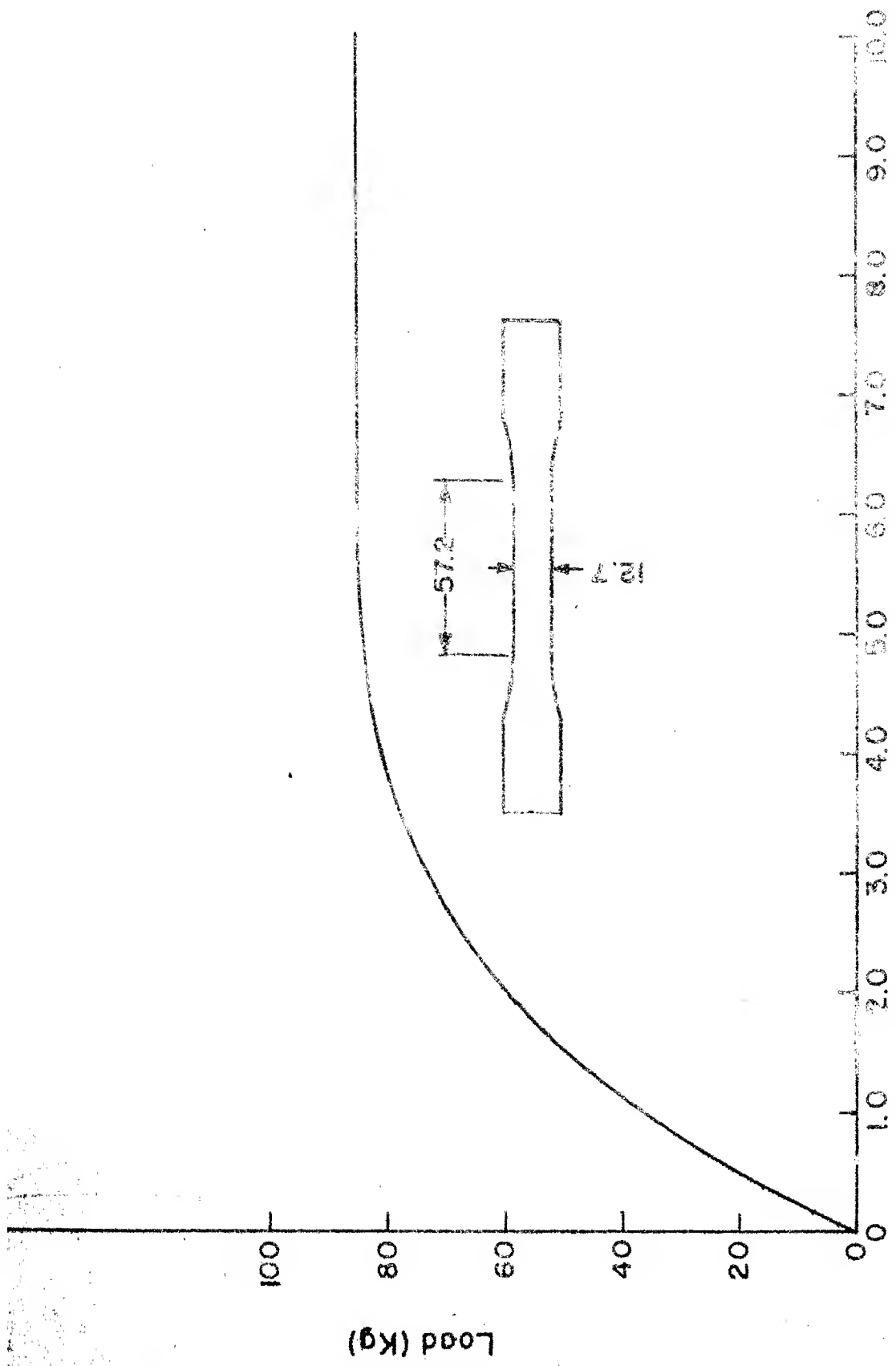
Dimensions In mm
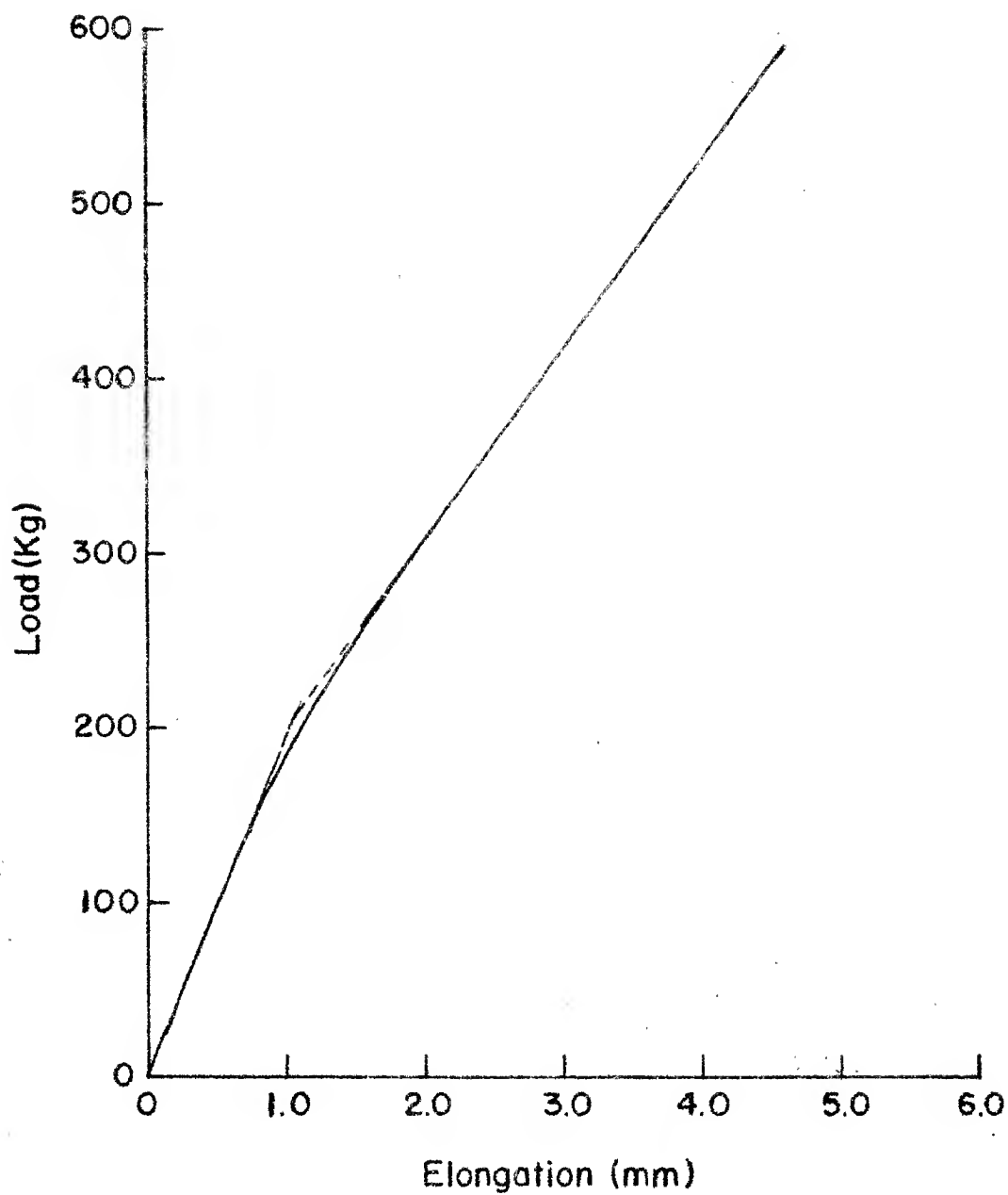
FIG. 4 : Load-Elongation curve for composite
with all the fibers parallel to the
load - axis. *(Vf = 0.091)*

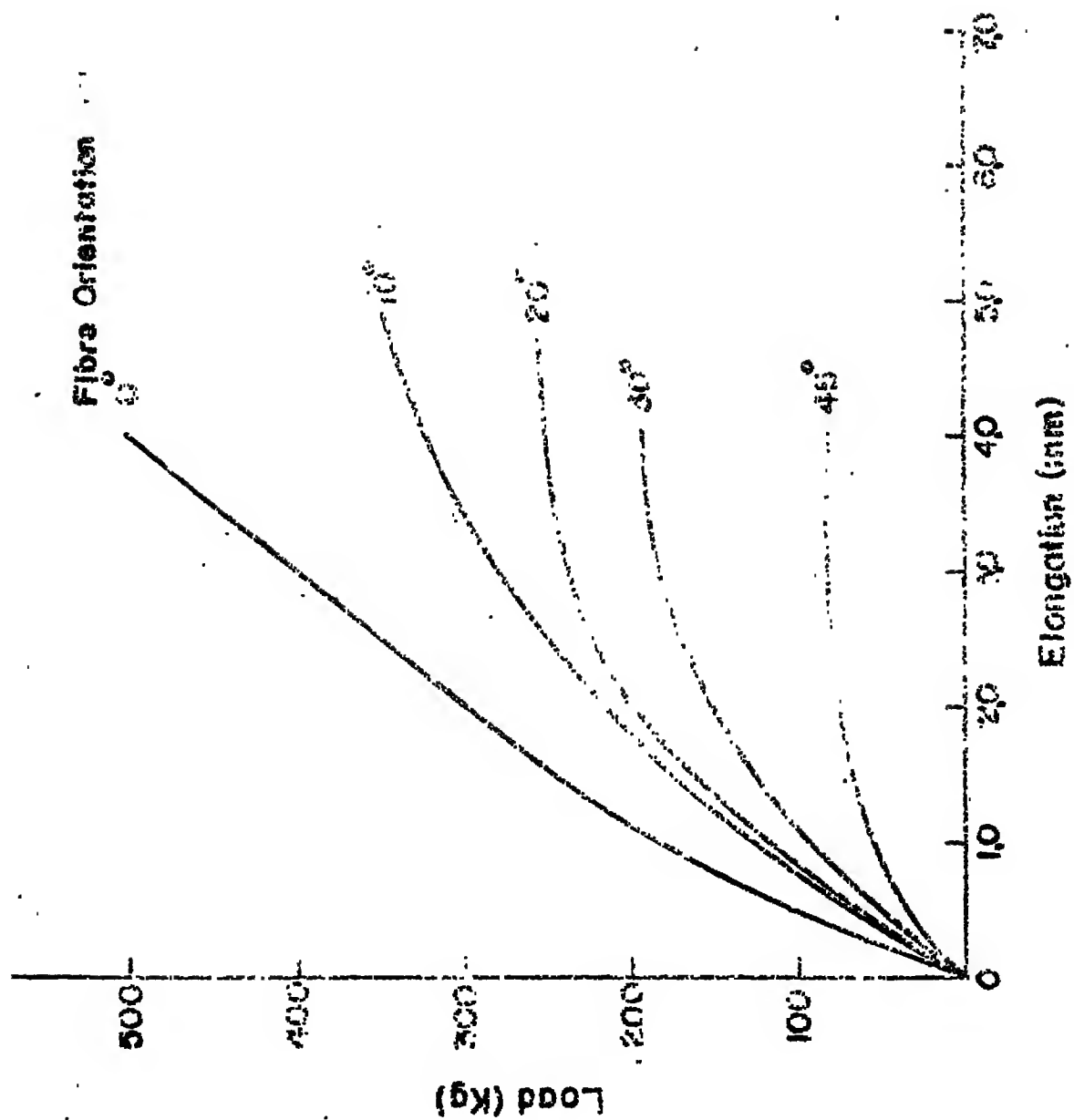FIG. 5 : Load-Elongation curve for composites
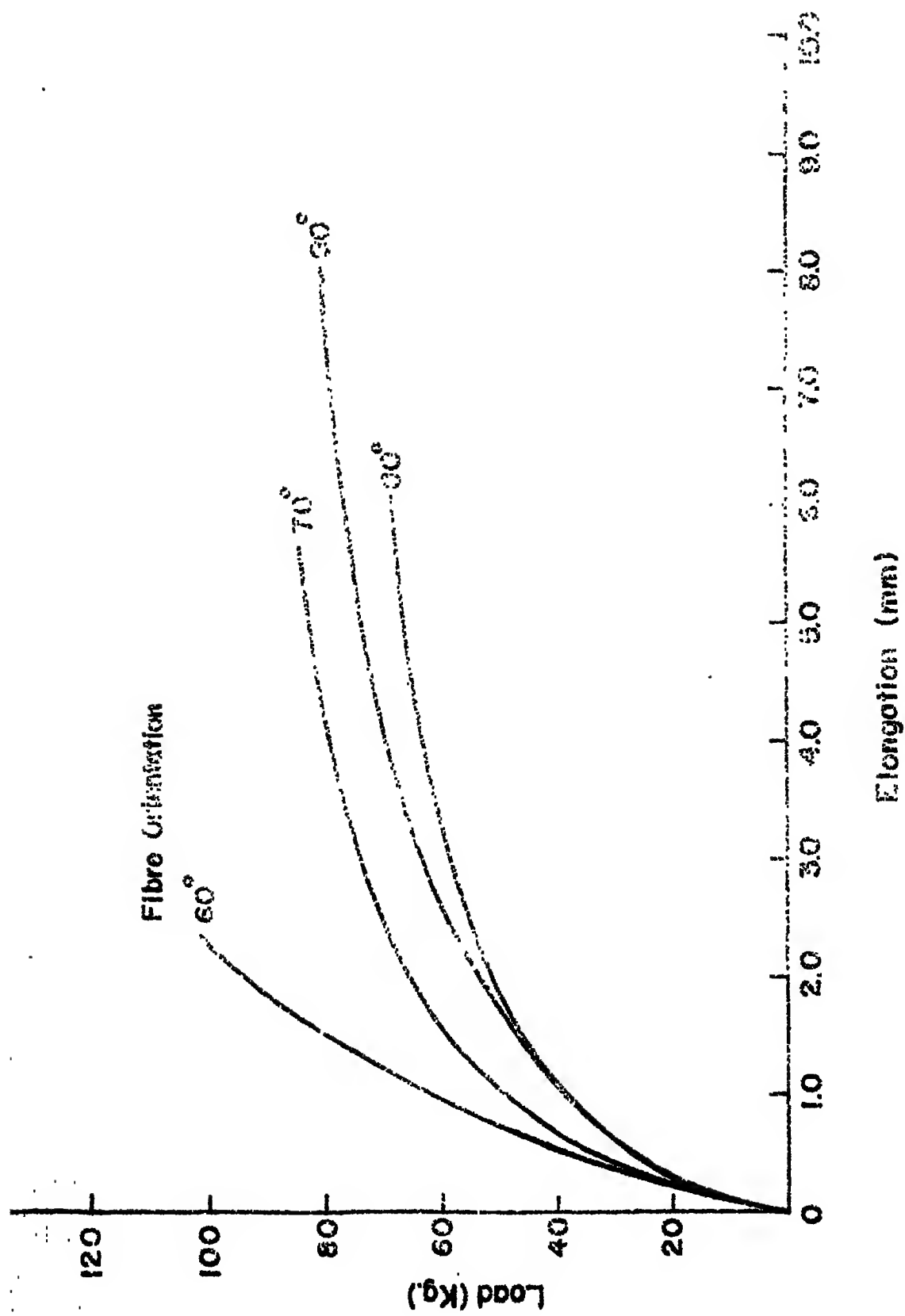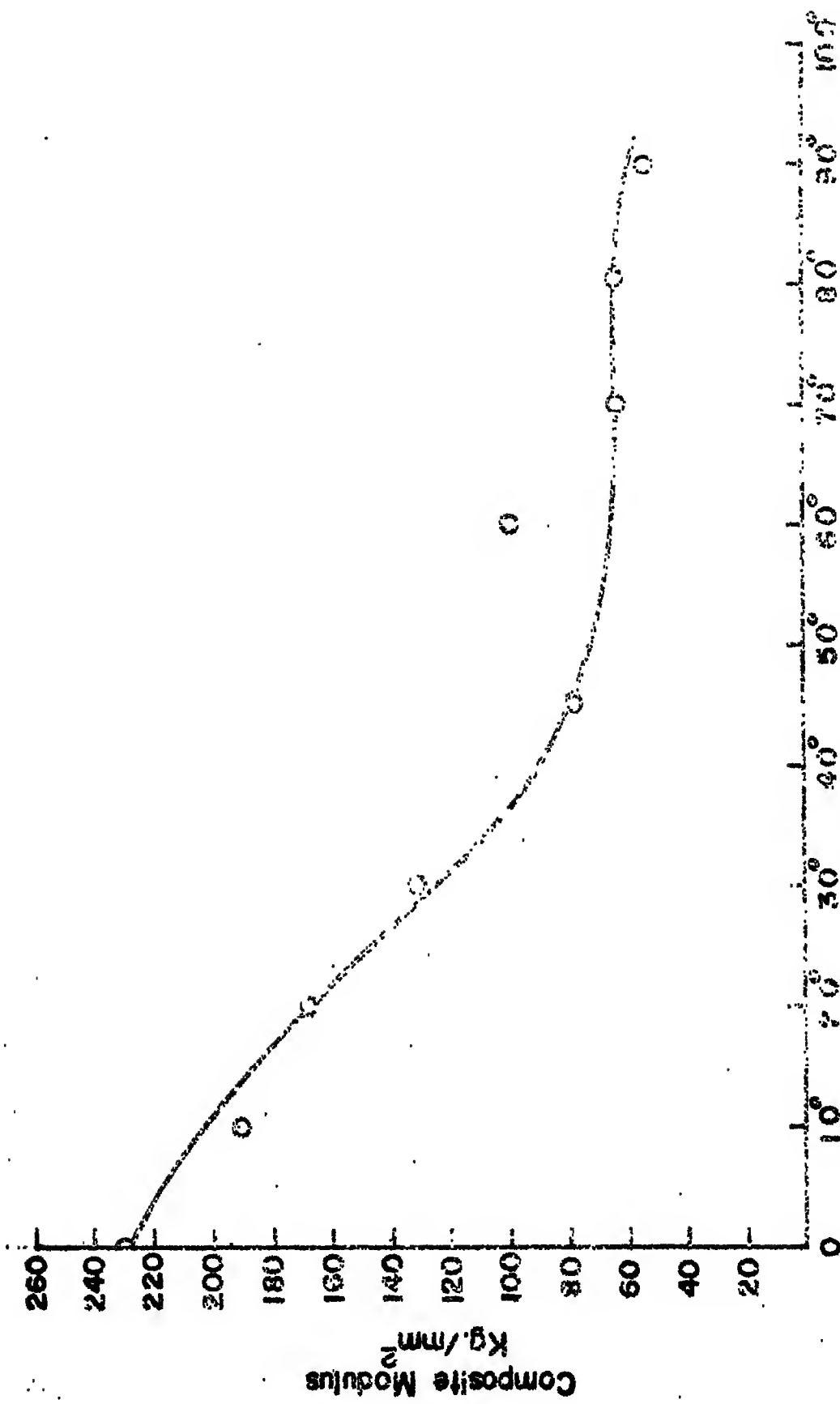
FIG. 6 : Load–Elongation curve for composites with fibres oriented at 60, 70, 80 and
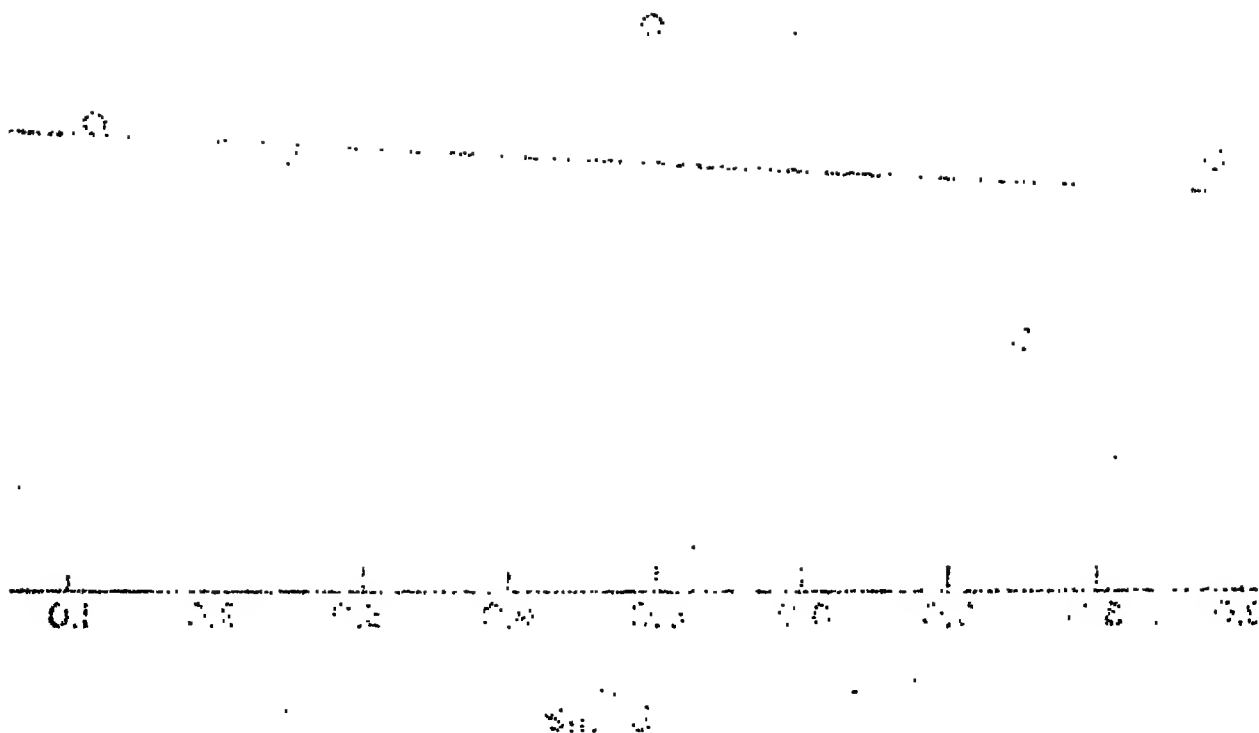
Fibre Orientation (Degrees)

Composite Modulus Kg./mm²

0.1

$Sin^2 \theta$

FIG. 8 : Plot of $\dfrac{E_o/E_\theta - 1}{Sin^2 \theta}$ Vs $Sin^2 \theta$
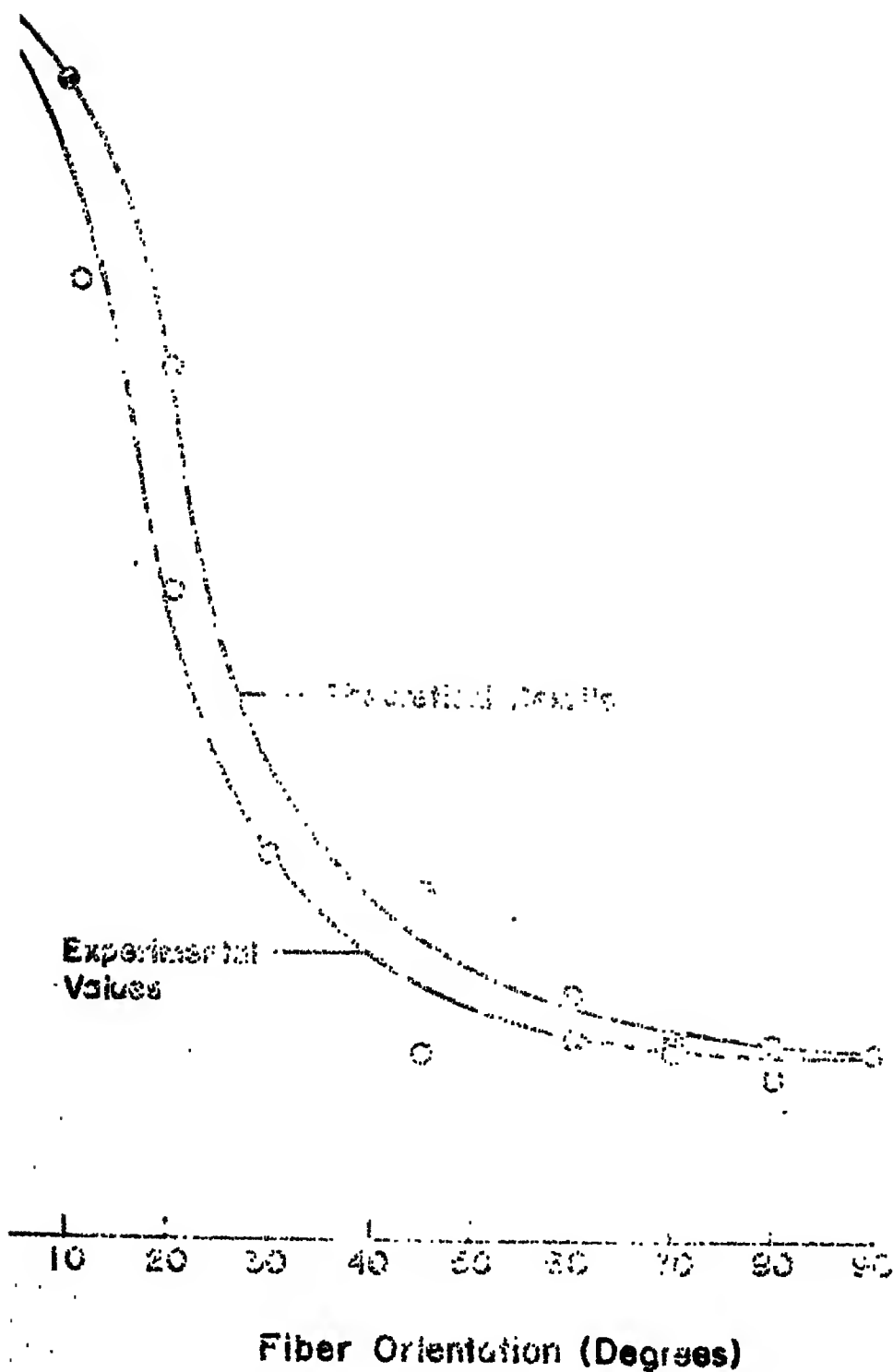
Theoretical Results

Experimental Values

Fiber Orientation (Degrees)

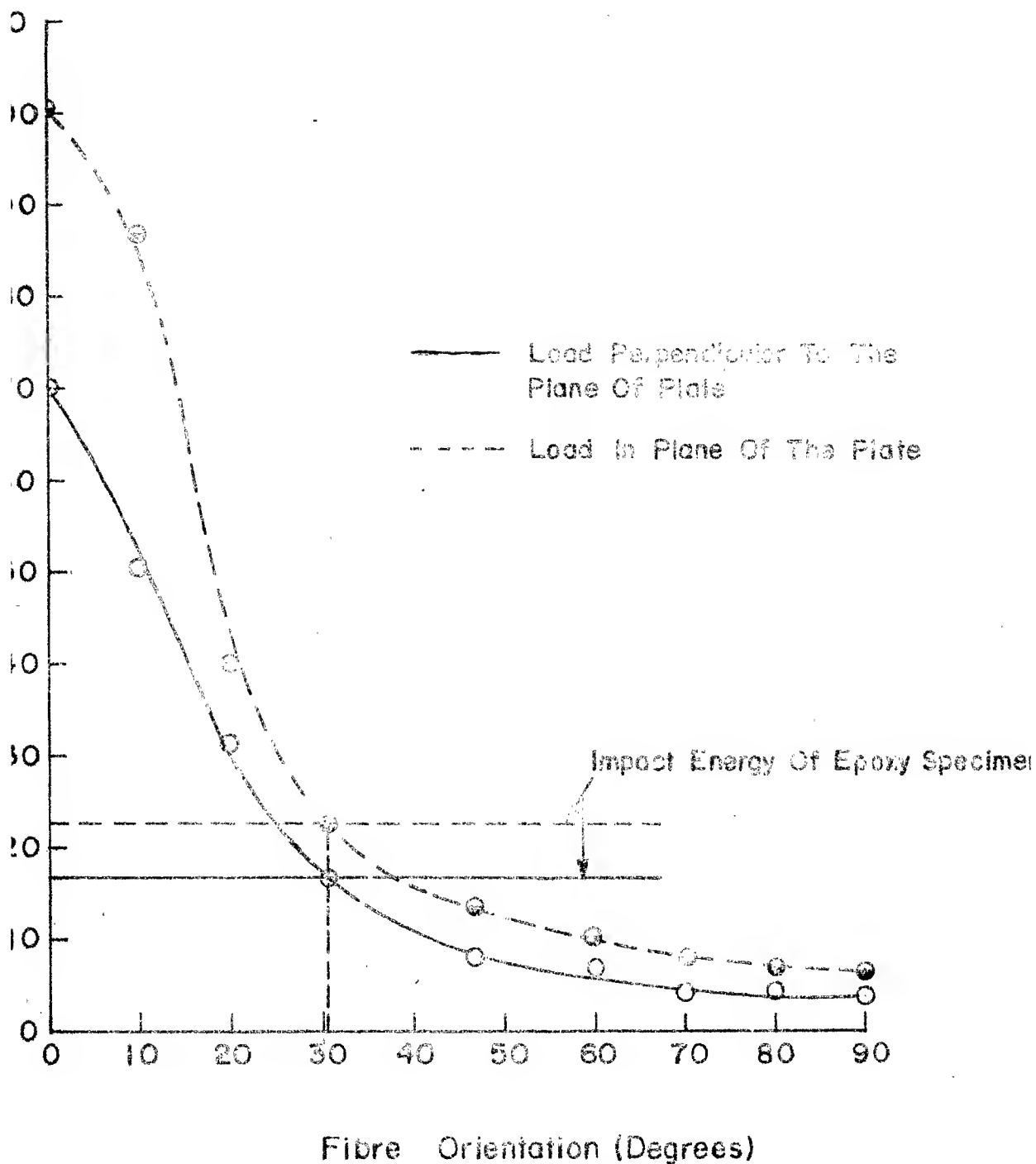FIG. 9 : Strength of the composites as a function of the orientation of fibers.

FIG. 10 : The Impact Energy of composites as a function of the orientation of the fibers.
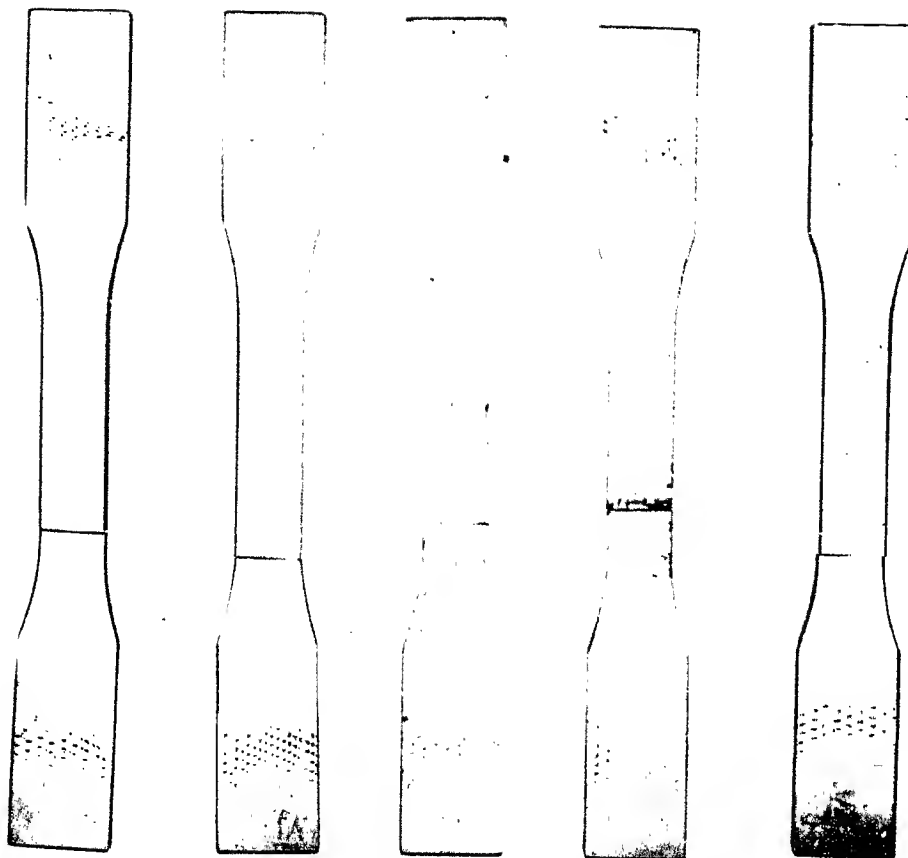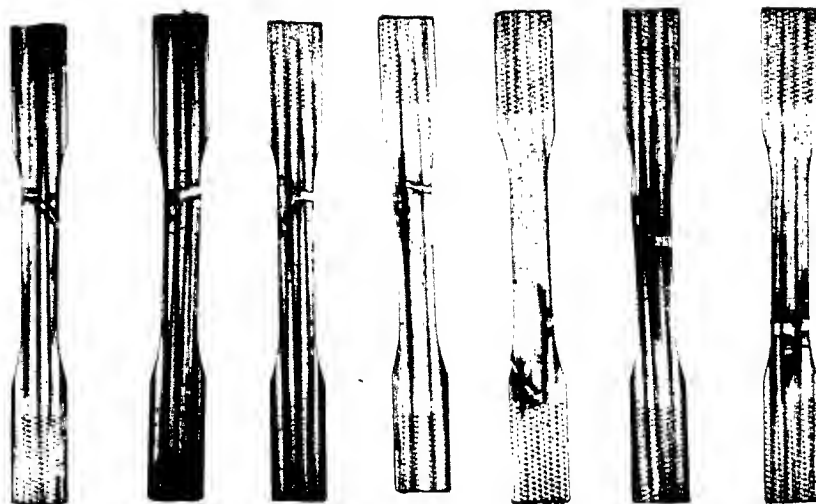
FIG. 11 : Fractured epoxy specimens under tensile
loading.

FIG. 12 : Specimens fractured under tensile loading (all the fibers parallel to the load - axis).

FIG. 13 : Specimens fractured under tensile
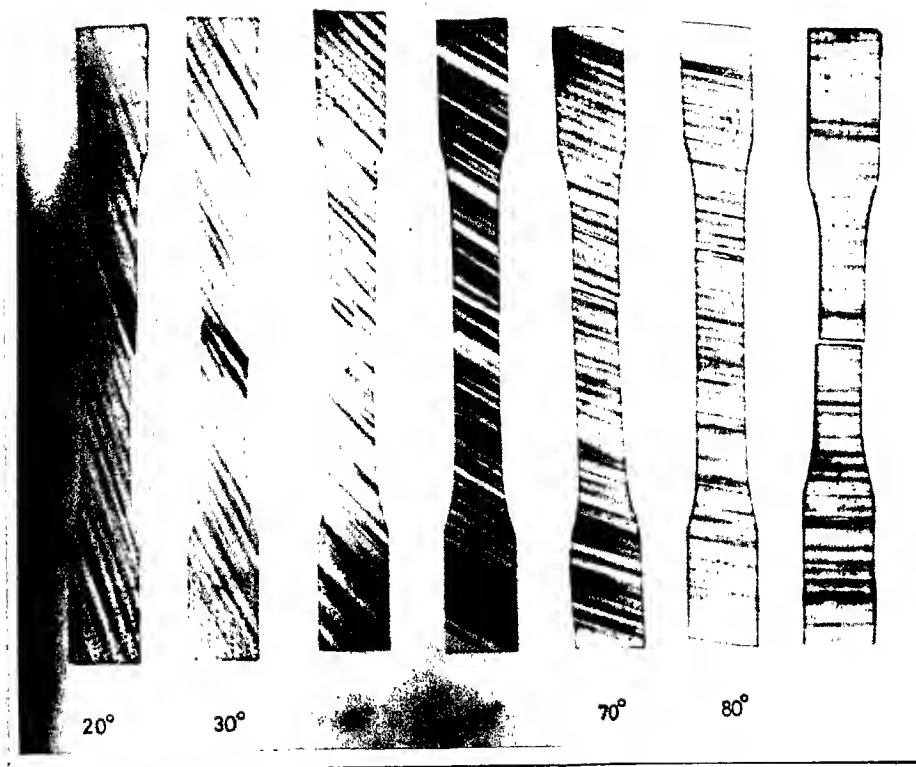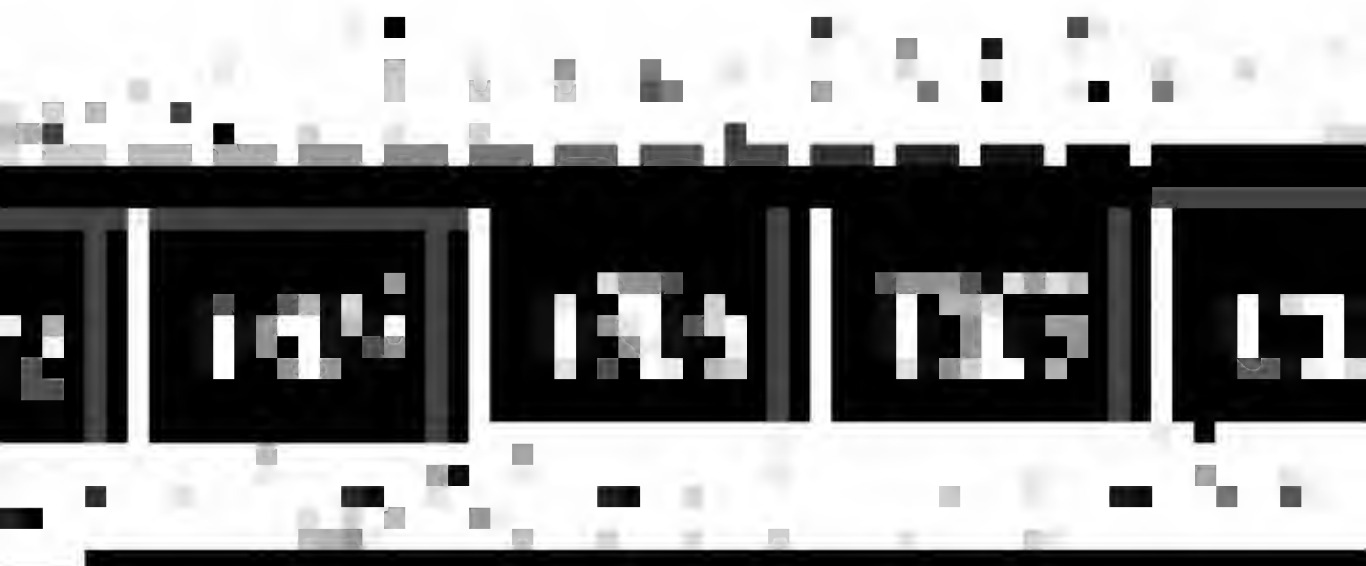   loading (fiber orientation = 10 degree)

FIG. 14 : Specimens fractured under tensile load-
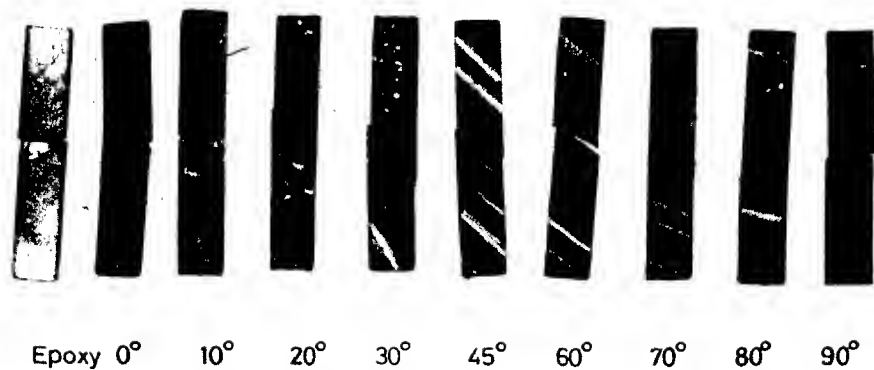ing (fibers oriented at 20 to 90
degrees).

Epoxy 0° 10° 20° 30° 45° 60° 70° 80° 90°

FIG. 15 : Specimens (with different fiber orientations) subjected to impact load perpendicular to the plane of the plate.

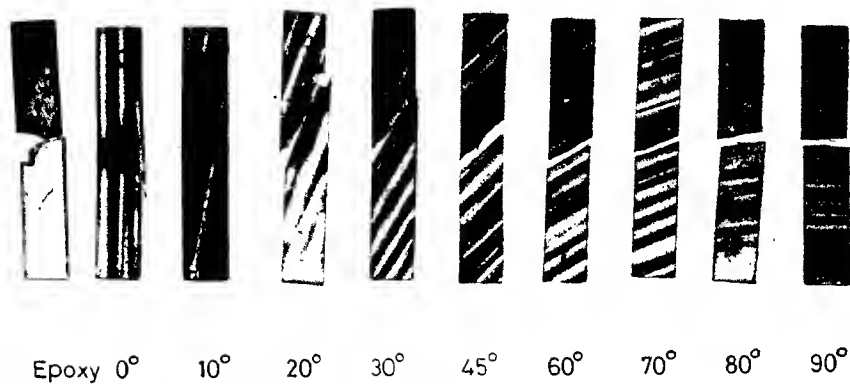Epoxy 0° 10° 20° 30° 45° 60° 70° 80° 90°

FIG. 16 : Specimens (with different fiber orientations) subjected to in plane impact loads.

Date Slip

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